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TRAMWAY SYSTEMS

CONSTRUCTION AND EQUIPMENT

DEVELOPMENT OF TRAMWAYS

HISTORICAL

1. Owing to the rapid growth of towns and cities, the economical and rapid transportation of passengers is a matter of great importance. In cities like London, Glasgow, and Manchester, the demand for travelling facilities during the hours when the people are going to or from their places of business is so great as to be almost impossible to meet. But the **electric tramways** have done much toward meeting this demand, especially for short distances; for distances greater than 4 or 5 miles, however, the steam and electric railways are preferred, because of the speed limitations of the tramways due to their running in the streets.

2. Early Tramways.—The first electric tramway was laid down by Messrs. Siemens & Halske at the Berlin Agricultural Exhibition in 1879. It consisted of a four-wheeled electric locomotive, drawing three small open cars that carried six passengers each. The locomotive was driven by means of a ring-wound geared motor, the current being collected from a central *third rail;* the two running rails acted as return conductors. It drew the train round a part of the Exhibition at a speed of 7 miles an hour.

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The first permanent tramway was built by the same firm in Berlin, in 1881. The track was $1\frac{1}{2}$ miles long, had a gauge of 1 metre, and the car carried 26 passengers at a normal speed of 13 miles an hour. The running rails and opposite wheels were insulated, for one rail acted as a feeder and the other rail as a return conductor. The motor weighed $\frac{1}{2}$ ton and developed $5\frac{1}{2}$ horsepower with a working pressure of 90 to 100 volts. The car and passengers weighed about 5 tons. This system was in operation until 1893, when it was superseded by the *overhead system*.

3. The first electric tramway in Great Britain was built by Magnus Volk at Brighton, in 1883. The current for the motors was collected from two insulated running rails at a pressure of 160 volts. This tramway is still in operation, but the current is now carried by a third rail, the two running rails acting as a return. In the same year, Messrs. Siemens Brothers built a 6-mile tramway at Portrush, Ireland, on the third-rail principle. The generating plant was driven by water turbines, making this the first electric-traction plant to be driven by water-power.

The first street tramway in England was constructed by Holroyd Smith along the sea front at Blackpool in 1884. This tramway, built on the *conduit system*, was about 3 miles long, and had a working pressure of 230 volts. Owing to various difficulties with this early type of conduit, and to the entrance of large quantities of water and sand into the duct, resulting in bad contact, the conduit system has been replaced by an overhead trolley.

4. American engineers began to turn their attention to electric traction in the early eighties. In 1883, Messrs. Bentley & Knight started an experimental tramway in Cleveland on a modified *trolley system*. The first tramway in America to use the modern trolley principle was constructed by Leo Daft in Baltimore, in 1885; a third rail was laid along the greater part of the line, however, and the trolley was used only at the road crossings and stopping places. At about the same time an overhead trolley system was shown by Van Depoele at the Toronto Exhibition.

5. Tramways and Light Railways Acts.—In England, tramway development was very slow from 1885 up to the early nineties, when the Leeds and South Staffordshire tramway systems were opened. This delay was due partly to the opposition of local authorities and partly to the great expense and onerous conditions imposed on tramways which were constructed under the Tramways Act of 1870, a special Act of Parliament being necessary for each project. The passing of the Light Railways Act in 1896 reduced the difficulty and the cost of obtaining powers to construct new tramways. Since that time, the development of electric tramways in the British Isles has been so rapid that at present about 3,000 miles has been constructed. Under this Act, tramways and light railways are broadly classified together. Thus, as far as the actual method of construction is concerned, an electric light railway may be in some instances merely an electric tramway constructed under the Light Railways Act of 1896.

POWER SUPPLY

6. Choice of Motive Power.—Electricity is now generally conceded to be the most convenient and economical power for the operation of street tramways. It is superior to horse, steam, and cable haulage, both as regards flexibility and cheapness of operation. Cable traction shows certain advantages in very hilly localities, but for general purposes electricity has the field practically to itself.

7. Transmission and Distribution.—Up to the present time, electric tramcars have been driven almost exclusively on the *direct-current system;* that is, the current supplied to the cars is direct, whether the current supplied from the generating station is direct or alternating. Where considerable power must be transmitted over long distances, alternating current is used for the transmission at high pressure, but it is transformed to low pressure and converted to direct current before being supplied to the cars. Where the distance of transmission is not very great, direct current may be supplied from the generating station; in this case, the use of alternating current is unnecessary.

8. The direct-current series motor is admirably adapted for traction work, and the principal reason why alternating current has not been used to any extent for tramways is that no equally suitable alternating-current motor has been available. The alternating-current induction motor is essentially a constant-speed machine, whereas the characteristics of a traction motor must include variable speed, large starting torque, and decreasing torque with increasing speed. The characteristics of the single-phase commutator motor are very similar to the series-wound direct-current motor. Certain conditions may arise in the future, in particular cases, which may make it desirable to use alternating current for tramway work, as it is already in use for railway work; at present, only direct-current apparatus and systems are standardized for tramway use, and the difficulty of changing over to alternating-current standards must considerably delay any change of system.

9. **Voltage of Supply.** — The maximum voltage at which current is supplied to the working conductor is fixed by the Board of Trade at 550 volts, although permission is granted to generate at any pressure up to 650 volts, in order to compensate for the drop in the feeder system. On most tramways, the average voltage of the working conductor is 500 volts.

METHODS OF CURRENT COLLECTION

OVERHEAD SYSTEM

10. **Alternative Systems.** — The most common method of supplying current to the car is by means of an overhead conductor, from which current is taken by means of a pole attached to the car; this is called the **overhead, or trolley, system.** The overhead conductor is known as the **trolley wire.** A method which makes use of underground conductors in a conduit, and supplies current to the car by means of a contact plough passing through a slot in the road surface, is called the **conduit system.** In the **surface-contact system,** current is supplied to a series of

contact studs placed between the tracks. These studs are so constructed that when the car passes over them they are made alive and current is collected from them by means of a *contact skate* carried on the car. A fourth method is by means of **storage batteries** carried on the car; in this case no conductors between the power station and the cars are necessary. Lastly, a third rail may be fixed by the side of the track rails; this third rail takes the place of the trolley wire in the overhead system. This is known as the **third-rail system** and is suitable only for private rights-of-way. Examples of third-rail tramways are often to be found on the piers at watering places.

11. **Advantages of the Overhead System.** — The overhead system is more widely used than any of the others, as it is both cheap and efficient. The cost of the line equipment is from one-half or less to two-thirds of that of other systems, while the cars and collecting arrangements are simpler and the leakage current less than in the conduit or surface-contact system. Some objection to it was raised on account of the unsightliness of the poles and the danger of falling wires; but the public soon became accustomed to the poles, while during 14 years the only serious accident that has taken place was caused by telephone wires falling and making contact with the trolley wires. Since this accident, the Board of Trade regulations covering the use of guard wires for the protection of telephone and telegraph circuits have been revised, so that there is now practically no danger from this cause. There is a certain amount of danger if a trolley wire breaks and falls to the ground, but the custom of anchoring the trolley wire at those points where breaks are especially liable to occur has minimized the danger from this source by preventing these wires from falling when broken.

12. **Diagram of Overhead System.**—A diagram of a simple tramway system, with an overhead trolley conductor supplied from a direct-current generator, is given in Fig. 1. The positive terminal of the generator is connected, through the switchboard, to the overhead trolley wire, and the negative terminal is connected to the rail return, the path of the current being indicated by the arrows. Current is collected by each moving car by

means of the trolley pole carried on the roof of the car. This simple arrangement was not devised without considerable experi-

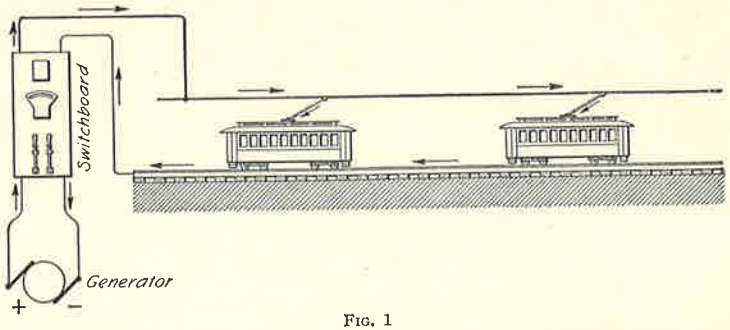

Fig. 1

menting. For instance, on some of the earlier tramways two trolley wires were used, no current being carried by the track rails.

13. Constant-Potential Supply.—All the tramcar circuits in Fig. 1 are electrically in parallel. This is true of all systems of distribution where current is supplied to the cars from a central source. All tramway systems are operated, therefore, at approximately constant potential; that is, constant or nearly constant pressure is maintained between the trolley wire and the track. Wherever a circuit may be formed from the trolley wire to the rail return, through the motors, a current flows and the car is propelled. Each tramcar is independent of all the others on the system, whether they are in motion or not, and each tramcar takes only just as much current as is required to drive it. The arrangement shown in Fig. 1 admits of many modifications. For example, except on very small systems, the trolley wire is not usually large enough to carry the whole current of the system; therefore, **feeders,** or heavy cables, are laid underground from the generating station to the trolley wire at various points. Return cables are sometimes used in combination with the track return.

CONDUIT SYSTEM

14. Principal Features and Construction.—The conduit system is the most expensive method of tramway construction, but it has the advantage of not requiring overhead wires. When the

conduit containing the conductors and the slot opening into it are placed midway between the running rails, the system is

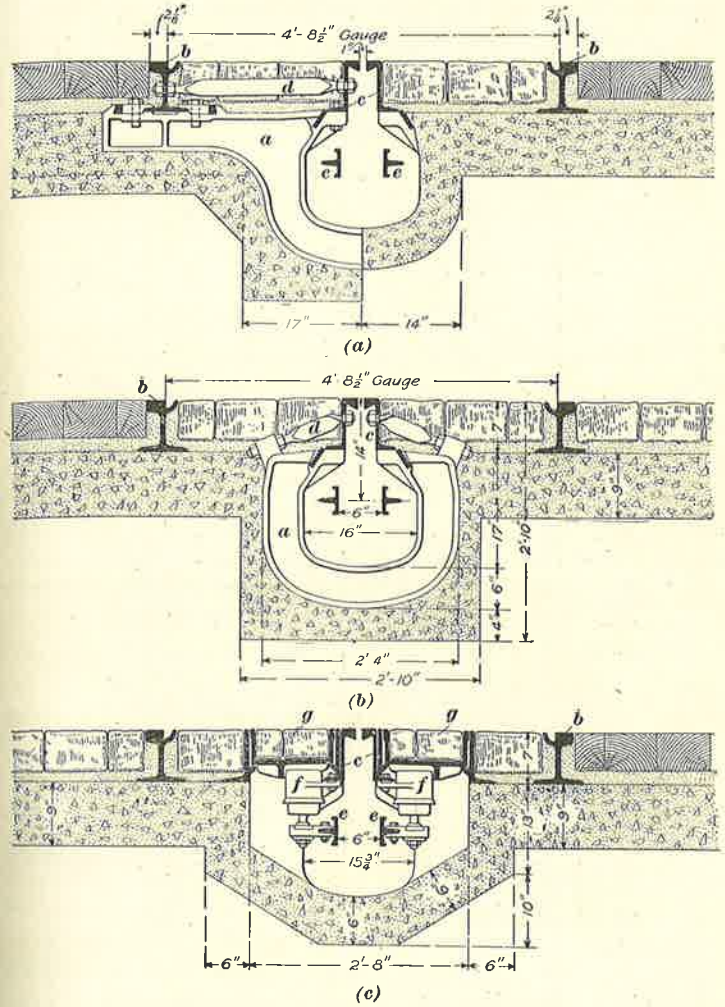

Fig. 2

known as the *central-conduit* or the *centre-slot system.* In the *side-slot system,* one side of the slot opening is formed by one of the running rails.

In Fig. 2 are shown sections of the centre-slot conduit constructed by the London County Council. The shape of the concrete conduit and the width of the slot are maintained by heavy iron *yokes a*, view (*b*), placed 3 feet 9 inches apart. Every second yoke is extended to support the running rails *b*, as shown

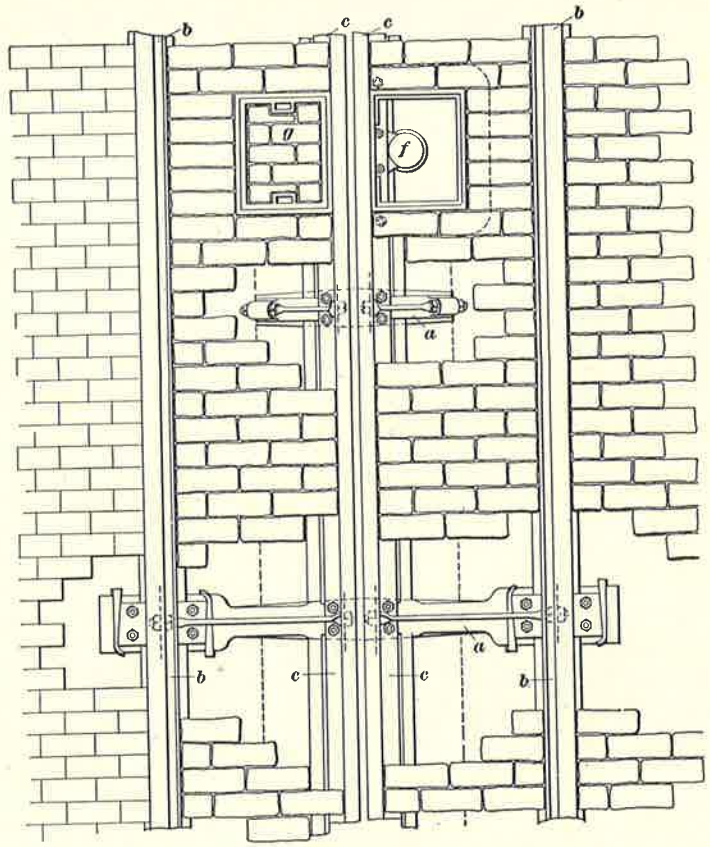

FIG. 3

in (*a*). The slot rails *c* are bolted to each yoke and are held rigidly in position by the tie-bars *d*. Two steel conductor rails *e*, which are of **T** cross-section, are supported on insulators *f*, view (*c*), placed in insulator boxes, which are spaced 15 feet apart. These insulator boxes have removable covers *g*, so as

to provide easy access to the insulators, which are bolted to the slot rails *c*. One conductor rail is positive and the other negative, so that the running rails are not used for carrying current. The conductor rails are divided into $\frac{1}{2}$-mile sections, which are insulated from one another by means of gaps left between the ends of the conductor rails. The conduit is made sufficiently deep so that mud and water entering the open slot will not reach the conductor rails, and at regular intervals drain connections are provided. The plan of a short length of track is shown in Fig. 3, in which the long and short yokes, the rails, etc., are given the same letters as in Fig. 2.

15. Collection of Current.—The current is collected by means of a *plough* carried by the car and which passes down through the slot to the conductor rails. Two cast-iron shoes, carried by the plough, press against the conductor rails, and cables lead from the shoes to the motors on the car. Fig. 4 shows the arrangement of a simple plough in relation to the conductor rails. Each contact shoe, as *a*, is pressed against the conductor rail *b* by a flat spring *c*. Cables *d*, *d* are connected through internal slots to the shoes; the cables lead to the motors and controlling devices on the car. The conductor rails *b*, *b* are supplied with current from the power station by outgoing and return feeders

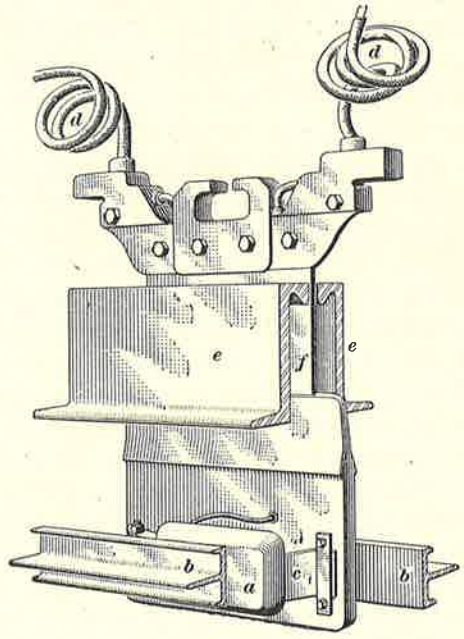

FIG. 4

run in ducts in the roadway by the side of the track. The narrow part *f* of the plough that is suspended between the slot rails *e*, *e* is made of steel, and renewable tempered-steel wearing plates are sometimes fastened at the points where the greatest wear occurs.

16. Disadvantages of Conduit System.—The conduit system works satisfactorily if the conduit is sufficiently strongly constructed and kept properly cleaned. Since there is very little clearance for the plough, however, in the slot and between the conductor rails, any breakdown that may occur, due to the plough fouling at points or crossings, entails much greater expense and time in clearing than could occur with the use of overhead conductors. The cost of construction is about twice that of an overhead trolley line, and it is only on lines having a heavy traffic that it can be made to pay. As the construction of the conduit in towns usually necessitates the removal or rearrangement of water and gas pipes, sewers, electric conduits, etc., that may lie in the path of the conduit, and which would not require removal in constructing the overhead system, the difference in capital cost of the two systems is still further increased.

SURFACE-CONTACT SYSTEMS

17. General Features.—In order to avoid both the overhead construction and the expense of building continuous and deep open-slot conduits, several surface-contact or stud systems have been devised. In these systems, *contact boxes*, or studs, placed at regular intervals between the running rails, are made alive by the passage of the car. This is usually done by strongly magnetizing a collecting skate carried on the car and by fitting a magnetic switch in each stud. After the car has passed the stud, the magnetic switch opens and the stud is left dead. The length of the skate and the distance between the studs are so arranged that the skate is always in contact with at least one stud.

In all surface-contact systems, special attention must be paid to the paving; the studs must not be so large, nor project so far, as to endanger the general traffic of the road, and yet the skate must make good contact with each stud and not interfere with the intervening paving. In the *G.B. surface-contact system* a special collector is used, which, to get over the paving difficulty, is made up of links; these are attracted to the studs in order to make contact and rise clear of them as soon as the studs are passed.

18. The objectionable features of surface-contact collection are the possibility of danger from live studs and the necessity of carrying heavy magnets on the cars, though in some systems the magnets are replaced by a striking bar on the car running in a slot or shallow channel in the road. The danger of live studs is being met by placing trailing attachments on the cars; these either short-circuit the faulty stud and cut off the current, or else indicate in the car when a live stud is left behind the car. When first installed, considerable trouble was caused by the car magnets picking up pieces of iron, which at crossings short-circuited the studs to the rails; this trouble is now avoided by insulating the running rails at these points.

19. Lorain Surface-Contact System.—The **Lorain surface-contact system** is in successful operation in Wolverhampton, and the danger from shock on account of the stud switches failing to work is not serious. A switch, which consists of two contacts, is placed directly beneath each contact stud or plate. The upper or fixed switch contact is connected to the stud head, and the lower or movable contact is in connection with the working conductor through a flexible copper ribbon. The lower contact is mounted on a thin iron plate, and a series of magnets suspended under the car, with their poles near the surface of the ground, attract this iron plate and draw up the lower contact against the upper one, thus establishing connection between the contact plate and the feeder. The contact studs and switches are placed 10 feet apart, and the magnets under the car are 16 feet long. Thus, one switch is always closed and the circuit through a second switch is always completed before the car leaves the first; the circuit is therefore not broken when a switch opens. The collecting skate is more than long enough

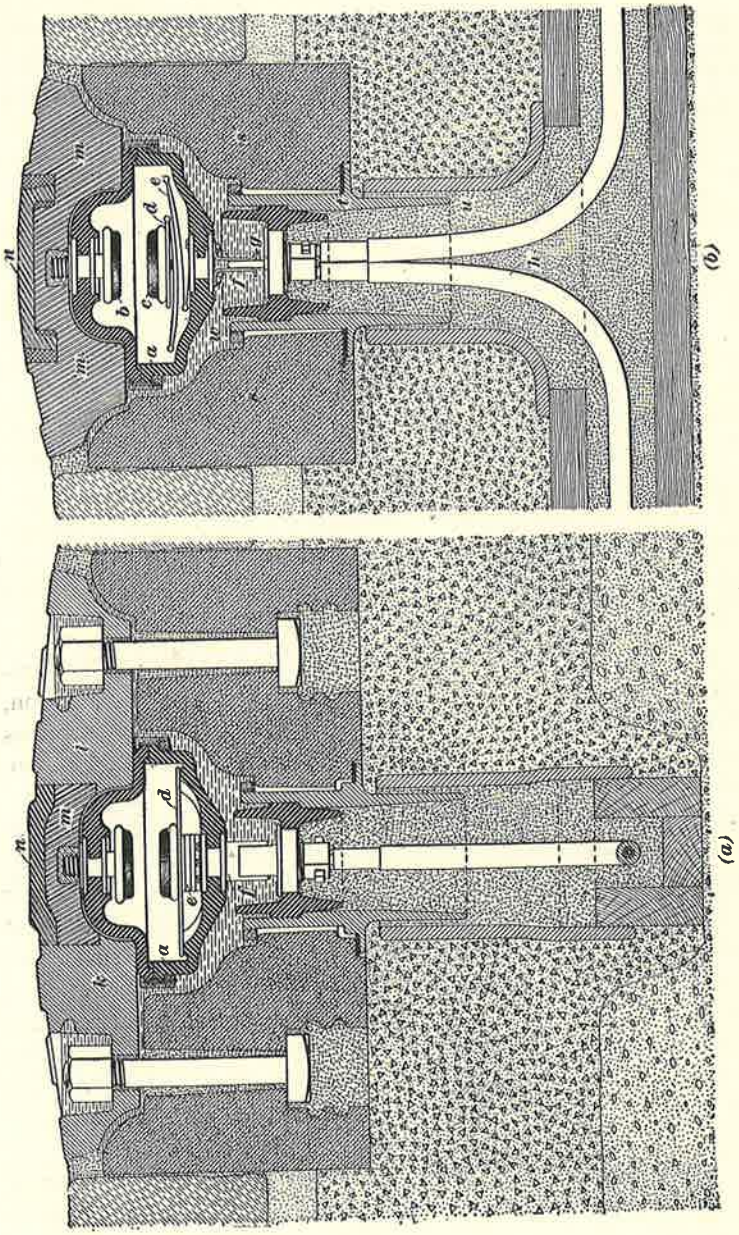

FIG. 5

to extend over two contacts, and there is thus a continuous collection of current. As soon as the magnets have passed over a switch, it again opens, leaving the stud dead after the car has passed. By making the switch contacts of carbon, there is very little danger of their sticking. A small storage battery is provided on the car to furnish current for energizing the magnets when the car is first started or to start the car after the current has been temporarily cut off from the line.

20. Lorain Stud Switches. — Transverse and longitudinal sections of the contact switches of the Lorain surface-contact system are shown in Fig. 5 (*a*) and (*b*) ; in Fig. 6 are shown the relative positions of the stud switch and the magnets on the car. The switch contacts, which are contained in a water-tight vulcabeston case *a*, Fig. 5, take the form of carbon discs, one, *b*, of which is fixed and the other, *c*, movable. The movable contact *c* is attached to an iron plate or armature *d* that is $4\frac{3}{4}$ inches long, 2 inches wide, and $\frac{1}{16}$ inch thick, and is electrically connected to the spring clips *f* through a folded copper strip *e*. The latter serves both as a flexible connection and also as a guide for the armature when it is drawn upwards by the magnets on the car. The feeder cable is brought up from a conduit below the track to the fixed switch tongue *g*, so that when the case *a* is in place, the movable contact *c* is in direct connection with the feeder *h*.

21. The cover of the switch box consists of four parts *k*, *l*, *m*, and *n*, Fig. 5 ; *k* and *l* are of cast iron and *m* and *n* of hard manganese steel, which is practically non-magnetic. The topmost section of the cover *n* takes the wear of the collecting skate and is renewable, being held in place by lead run in round it. The switch contact case is fastened to plate *m*, so that by removing the cover the whole case can be lifted out and disconnected from the live feeder. The cover as a whole is bolted to a strong block *s s* of *reconstructed granite*, that is, a block composed of cement and finely broken granite. The feeder cable passes into the switch box through a cast-iron sleeve *t* that fits into a **Y** casting *u* ; both of these *t*, *u* are filled with insulating compound. The space *w* surrounding the switch contacts *f*, *g* is

filled with a heavy insulating oil that prevents moisture from accumulating and thus minimizes surface leakage.

22. Working of Lorain System.—The operation of the stud switch will be understood from Fig. 6, where *M* represents one of the magnets carried on the tramcar; the parts of the switch are lettered to correspond with Fig. 5. Six magnets altogether are suspended under each car, the end magnets being the full length of the skate, or 16 feet, apart. As the pieces of manganese steel *m*, *n* between the side blocks *k*, *l* are practically non-magnetic, when a magnet is over a switch, as in Fig. 6, the lines

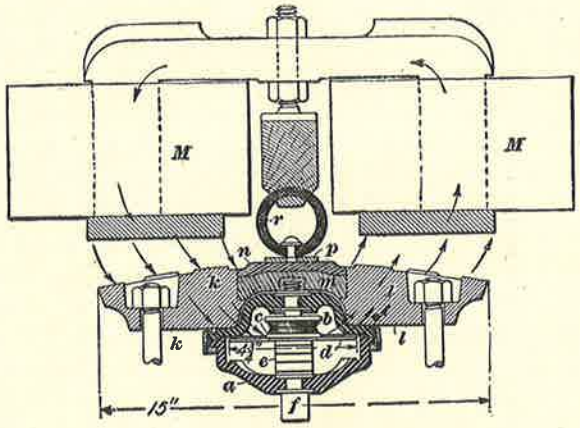

FIG. 6

of force take the path indicated by the arrows and pass through the light armature *d*, drawing it upwards, and thus bringing the carbon contacts together. As soon as the magnets have passed away from the stud, the armature *d* drops, and since the contacts are of carbon there is very little danger of their sticking. The collecting skate consists of a flat steel or copper strip *p* bent up at each end and fastened to a piece of heavy rubber hose *r*, which provides pressure between the skate and the studs. The skate is long enough to bridge across two contact studs, thus providing a continuous collection of current. The magnets are compound-wound. When the car is at rest, the shunt winding

is excited either from the line or from the storage battery carried on the car, and keeps the contact switches closed, so that the car can be started; the series winding provides excitation in case the supply voltage falls too low for the shunt winding to operate the switches; it also holds the switches more firmly in contact as the current taken by the car increases.

23. Dolter Surface-Contact System.—In Hastings, Torquay, and Mexborough the **Dolter surface-contact system** is in use. The Dolter stud switch box *a*, Fig. 7, is fitted with a manganese-steel cover-plate *b*, which carries two magnetic-steel pole pieces *c*.

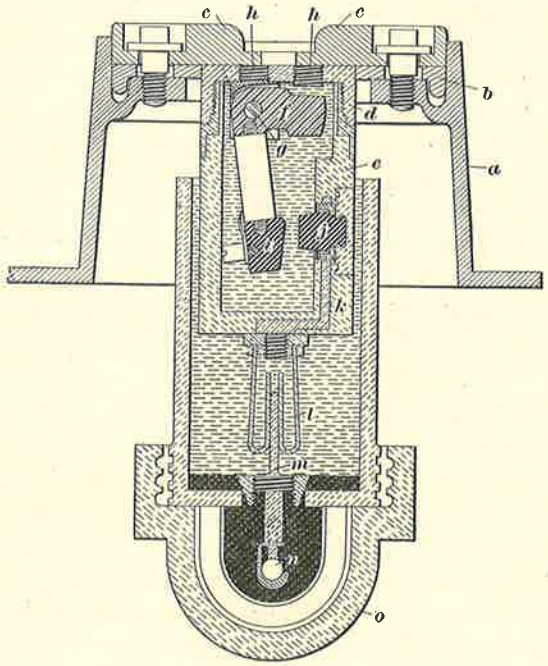

FIG. 7

These pole pieces form part of the magnetic circuit, manganese steel being non-magnetic. Underneath the cover-plate *b* is attached a gunmetal casting *d*, which in turn supports a pot *e*, made of insulating material, and a rocking lever *f* hinged at *g*.

Into the gunmetal casting *d* are fixed two steel plugs *h*, which also form part of the magnetic circuit. Carried by the lever *f* is a carbon contact piece *i*, which, when the upper end of the lever is drawn magnetically toward the plugs *h*, makes contact with a fixed carbon block *j* on the side of the pot. The contact *j* is electrically connected, by means of the strip *k*, to the spring clips *l*, which fit over a tongue *m* coupled to the feeder cable *n*. The latter is laid in an earthenware trough *o*, which is then filled in with bitumen. In order to prevent water from reaching the contacts *l*, *m*, the box surrounding them is filled with heavy oil.

24. Working of Dolter System.—The studs in the Dolter system are operated by a magnet attached to the car, as in the Lorain system. As the magnet passes over each stud, the lever *f*, Fig. 7, is attracted upwards, the carbon blocks *i* and *j* make contact, and the current passes from the cable *n* to the stud and then through the collecting skate to the controllers and motors. The studs are placed about 9 feet apart and the skate is always in contact with one of them; when the car has passed the stud, the lever *f* falls back by gravity to the off-position. As a safeguard against leaving live studs behind the car, a brush attached to the car framework makes contact with the stud after the magnet has passed it; if the stud is alive, a fuse in the stud circuit is blown and the current is cut off.

25. The skate collector, carried on the car in the Dolter system, consists of two long parallel bars hung low enough just to touch the studs. The skate bars are magnetized with opposite polarity by three electromagnets placed between them. As the position of the bars is immediately over the pole pieces *c*, Fig. 7, the magnetic circuit is completed from the bars through the pole pieces *c*, the studs *h*, and the top portion of the rocking lever *f*. The magnets are normally energized by current from the working conductor; should the current be cut off the cable for any reason, the switch levers will fall to the off-position, so that a small storage battery must be carried on the car to energize the magnets and pick the switch levers up again. When they are picked up, the main current is again available for energizing the magnets.

26. G.B. Surface-Contact System.—One of the cheapest surface-contact systems to install is that known as the **G.B. surface-contact system**, so called from the initials of its inventors. It is in use in Lincoln. The conductor is a $1\frac{3}{16}$-inch steel cable placed in a glazed earthenware pipe, about 5 inches in diameter, which is laid underneath the track. This conductor practically takes the place of the trolley wire in the overhead system, and is supplied with current from the generating station in a similar manner. Immediately over the conductor, and at intervals of from 6 to 9 feet, are placed the studs, which are constructed so that, when a magnet carried on the car passes over them, a small floating armature is forced against the conductor and by making circuit with the cable the stud is energized.

27. Stud of the G.B. System.—Transverse and longitudinal sections through the stud of the G.B. system are shown in

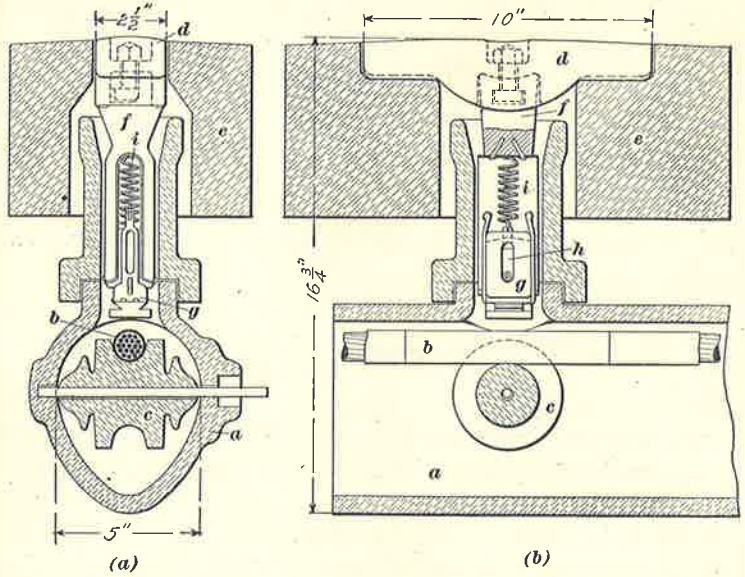

FIG. 8

Fig. 8 (*a*) and (*b*). The earthenware pipe *a* protects the conductor *b*, which is supported on the earthenware insulator *c*. Projecting downwards from a cast-iron stud head *d* set in a

granite block *e* is a brass-lined cast-iron fork *f*. A galvanized-iron floating armature *g* works within this fork; its movement is limited by small pins that work in the slot *h*. The armature *g* carries a carbon contact-block held in a copper clip, and is normally kept from making contact with the conductor by a light spiral spring *i*. Flexible copper leads connect the copper clip with the main portion of the stud. When the car magnet passes over the stud, the lines of force pass through the stud and the forked projection to the steel conductor. The small floating armature sets itself against the pull of the spring *i*, so as to bridge the gap between the fork and the steel cable, and energizes the stud through the flexible copper connections. In order to prevent any injury to the strands of the working conductor through arcing at the switches, short sleeves of galvanized steel are slipped over the conductor throughout its whole length.

28. Working of the G.B. System. — The car equipment of the G.B. system consists, as usual, of a means of collecting the current and a magnet for operating the studs. The magnet is fixed rigidly to the car body and is connected to a storage battery carried on the car. The collector consists of a number of iron links suspended from a wire rope which takes the place of the usual rigid skate; when a stud is magnetized, these links are attracted and bear on the stud, thus conveying the current

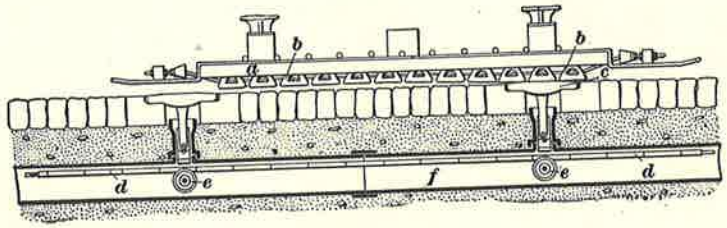

FIG. 9

to the car. When clear of the stud the links are drawn up out of the way of the paving. This arrangement allows the studs to be placed nearly flush with the roadway. In Fig. 9 is shown a longitudinal section of the collector. A rigid bar *a* running the whole length of the collector forms the magnet poles. It also

supports the iron links *b*, which are attracted toward the stud *c*; *d* is the working conductor, *e* the supporting insulator, and *f* the earthenware pipe enclosing the conductor.

29. Robrow Surface-Contact System.—A system in use on the Continent and in India, and which differs from those just described, is the **Robrow surface-contact system**; in it, the switches controlling the supply of current to the studs are operated mechanically. In Fig. 10 is shown a section through the track at a stud and switch box. The contacts of a water-tight switch *a*, which is enclosed in a cast-iron box *b*, are closed by a lever *c* that is operated by a bar *d* fixed to the car. When the car has passed, the lever springs back and the switch returns to its normal open position. The current passes from the feeder *e*, through the switch and a short cable *f* to the stud *g*, which is set in a granite block *h*. The car equipment consists of a skate *i*, fixed in the centre of the car and long enough to make contact with two studs at the same time. The operating bar *d*, which keeps the stud switch closed while the car is passing over it, is a little longer than the skate and is attached to the

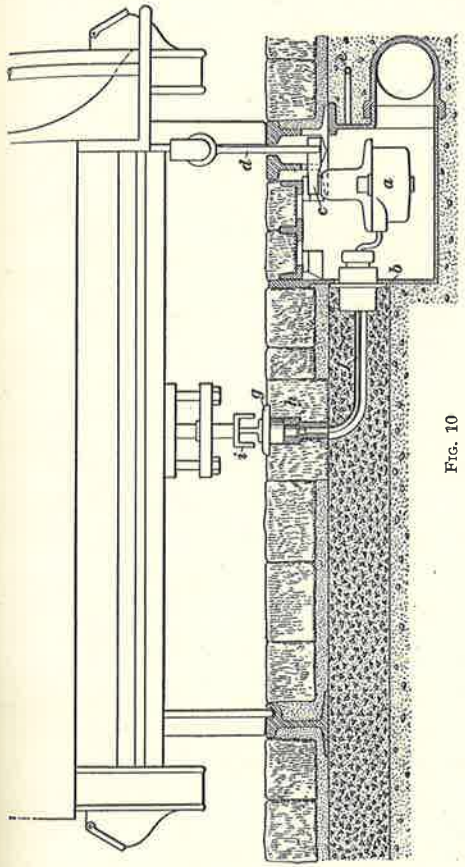

FIG. 10

side of the car truck. The advantages of this system are that the switches can be substantially made, as they are operated mechanically, and also there is no heavy magnetic gear to carry on the car. Against these advantages must be set the cost of the double rail forming the slot in the road and the consequent labour of keeping the slot clean, and also the disadvantage of having a long operating bar attached to the truck.

STORAGE-BATTERY SYSTEM

30. Limitations of Use of Storage Batteries.—Many attempts have been made to work electric tramcars by means of storage batteries carried on the cars, but none of them have proved successful. The constant vibration of the cars soon causes the cells to deteriorate, while the acid fumes given off are both offensive and destructive. For some special kinds of traction work, batteries have proved desirable, as, for example, the operation of electric shunting locomotives for use on manufacturing works or electric generating stations.

Batteries may often be used to great advantage, however, on tramway systems when they are placed in power houses or substations to take up fluctuations in the load or even to carry the whole load for short intervals. In work of this character, where the battery is stationary, the deterioration is not nearly so rapid as when the cells are subjected to vibration and shocks on a car. Moreover, a stationary battery can be made heavy enough to secure durability, whereas a tramcar battery must be made as light in weight as possible, at the expense of durability. Even when the batteries carried on a tramcar are made as light as possible, the storage and driving equipment of the car become extremely heavy compared with the corresponding weight for most of the other systems of driving, either electrical or mechanical.

THIRD-RAIL SYSTEM

31. Contact Rail and Shoe.—In the third-rail system, current is conveyed to the moving cars by a third rail mounted on insulators at one side of the track and slightly above the level

of the running rails. Current is collected by the car by means of shoes that slide on the contact rail; the return path of the

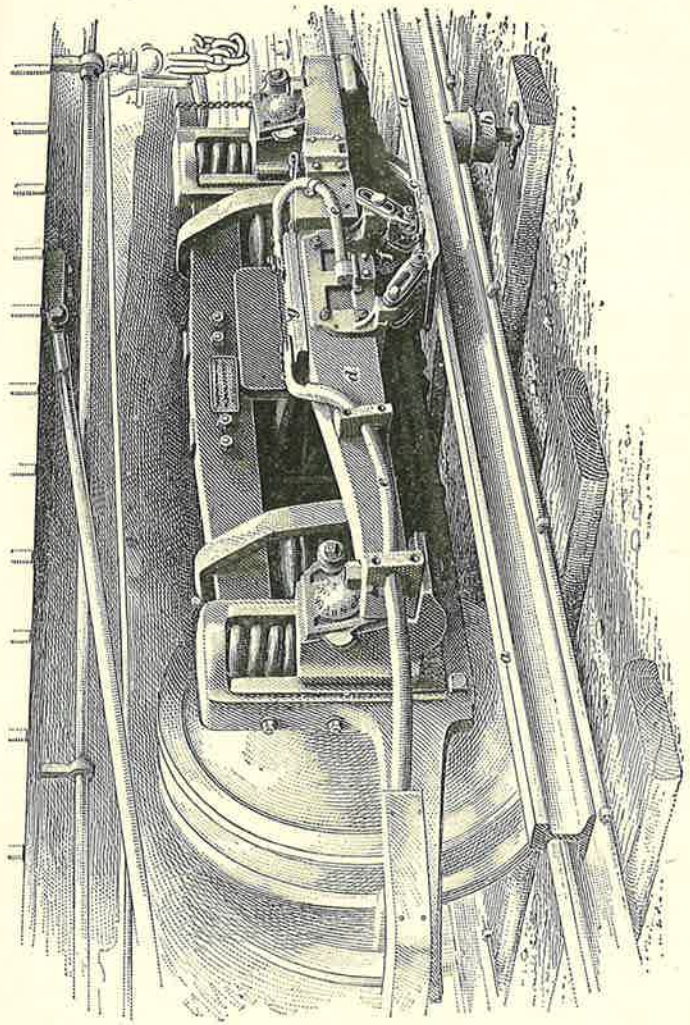

FIG. 11

current is through the track rails, as in the overhead system. In Fig. 11 is shown the arrangement of the contact or collecting shoe on a typical third-rail line. The third rail *a* is of girder

section, and is supported on insulators *b* resting on every fifth sleeper, which is extended for this purpose. The cast-iron collecting shoe *c* is suspended from links, so that it is free to move up and down through a limited range, in order to follow any inequalities in the surface of the third rail, and the whole collecting device is attached to a wooden beam *d* carried by the truck. Cable *e* leads to the controllers and motors on the car, and electrical connection is maintained with the shoe by means of the bare flexible copper cable *f*. The mechanical links are not depended on to carry the current. In some cases, a copper fuse is placed at *g* to cut off the current in case of short circuit.

TRANSMISSION AND DISTRIBUTION OF CURRENT

DIRECT- VERSUS ALTERNATING-CURRENT TRANSMISSION

32. Simple Direct-Current Transmission. — The simplest method of distributing current to the tramway tracks is by direct current transmitted from the generators without the use of any intervening transforming or converting devices. The distance beyond which it becomes uneconomical to transmit current at 500 volts for traction purposes depends on the load to be dealt with. The Board of Trade limit the load which may be carried by any one feeder to 300 kilowatts, which is equivalent to 600 amperes at 500 volts. Moreover, the drop in the return rails must not exceed 7 volts, and the current density in the rails must not be more than 9 amperes to the square inch; in the case of two 95-pound rails forming a single track the maximum current on this basis would be about 170 amperes. When the drop of 7 volts in the rail return is likely to be exceeded, negative boosters must be used for the return current; and when the drop in the positive feeder will be excessive, positive boosters also must be used.

33. Alternating-Current Transmission. — For transmission beyond a certain distance, it is usually more economical to

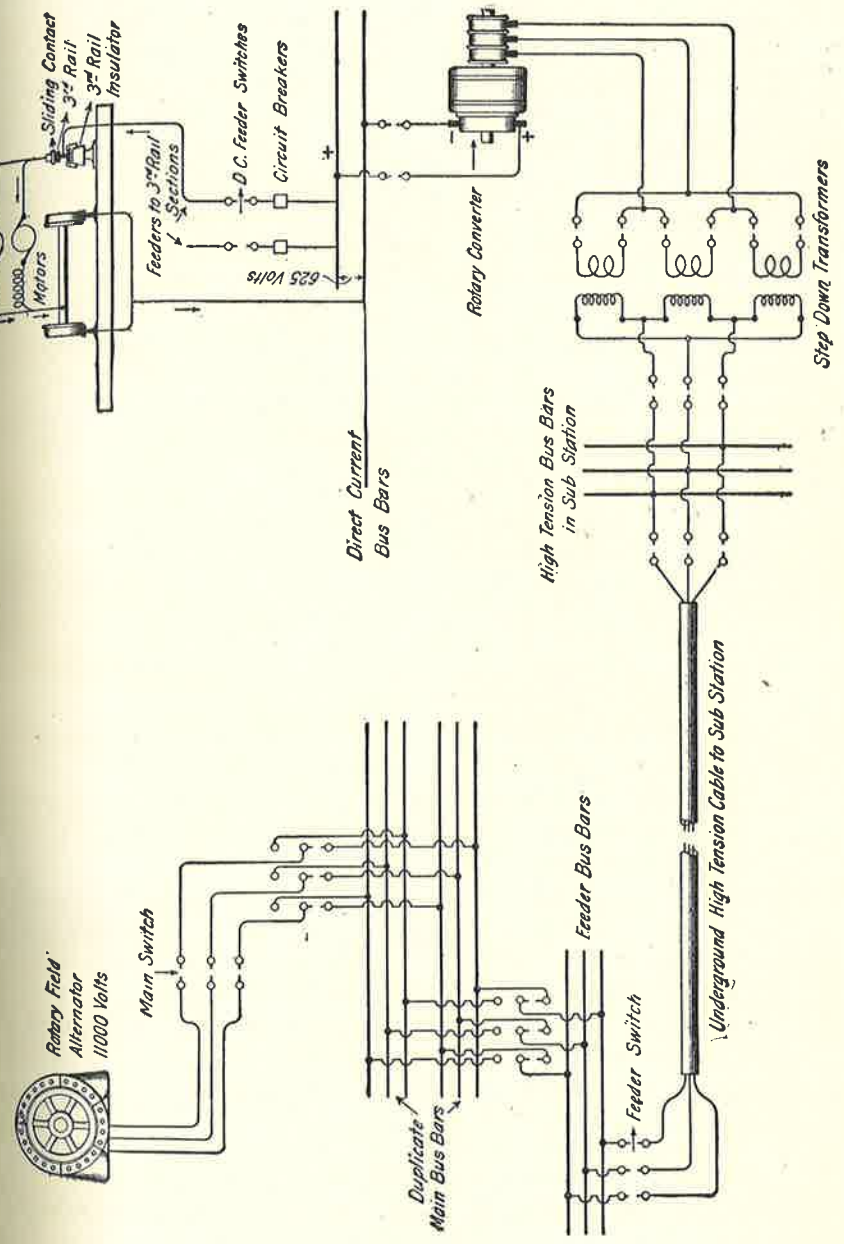

FIG. 12

generate at high pressure and transmit to a substation. In such a case, the high-tension transmission is usually carried out by three-phase alternating current, at a voltage probably between 5,000 and 6,500 volts. The high-tension current is conveyed from the power station to the substation through three-core cables laid underground. At the substation, the current is transformed to low-tension alternating current, which is then converted to direct current at 550 volts by means of rotary converters. Alternatively, motor generators may be used, in which case the static transformers are unnecessary, and the full alternating-current voltage is applied to the motor which drives the direct-current generator. Rotary converters are used on the Glasgow tramways, the London United tramways, and the London Underground railways, while motor generators are used on the London County Council and on the South Lancashire tramways.

34. Diagram of Extra-High-Tension Transmission System.—In Fig. 12 is shown a diagram of an extra-high-tension transmission system, using transformers and rotary converters in the distant substation, similar to those used by the London Underground railways. The current is generated in a central station by revolving-field three-phase alternators direct-connected to 8,000-horsepower engines. The use of the revolving-field type of machine is necessary to enable the current to be generated at 11,000 volts in the machine, and so to save any transformation at the generating station. The current is distributed by means of heavily insulated lead-covered cables, laid underground in conduits, to a number of substations, and is there transformed to low voltage. Rotary converters in the substations convert the alternating current to direct current at about 625 volts, and from the substations it is supplied to the cars by means of a third rail laid along the ordinary track. The third rail would be replaced, in the case of most tramway systems, by an overhead trolley wire, or the working conductor of the conduit or surface-contact systems.

35. Choice of System.—The question as to the exact load point at which it is advisable to install boosters for direct-current

transmission over moderate distances, and when to adopt high-tension transmission, must be considered for each particular case. The capital cost of each system must be estimated, and the annual capital charges must be compared with the cost of the energy lost in transmission. The more economical method is that in which the annual cost of the wasted energy equals the annual interest on the capital expended, plus an allowance for depreciation. With a simple 500-volt direct-current distribution, the cost of the energy lost may be calculated from a knowledge of the load to be dealt with and the resistance of the conductors, positive and negative. When boosters are used additions must be made to the losses, equal to the losses in the boosters themselves, while both the amount and the rate of depreciation must be increased owing to the increased capital cost and the introduction of moving machinery. Where high-tension transmission is adopted, there must be considered the cost of the losses in the high-tension line, in the transformers, rotary converters, and the low-tension system.

ESTIMATE OF POWER REQUIRED

36. Tractive Effort and Tractive Resistance.—The propelling effort exerted by the car motors to keep a car in motion, and applied by the wheel tires on the head of the rail, is called the **tractive effort** and is usually expressed in pounds pull. To maintain motion, this effort must be equal to the sum of the forces which oppose the motion. The frictional and wind resistances which oppose uniform motion on the level are collectively known as the **tractive resistance.** This resistance depends on the condition of the rails, the efficiency of the car mechanism, and the resistance of the wind. The wind resistance is variable, but the other two factors are constant enough, at ordinary tramcar speeds, for one to choose an average force, such as 20 pounds, per ton of weight necessary to maintain motion.

Let f = tractive resistance, on level track, in pounds per ton;

W_t = weight of tramcar, in tons;

F = total tractive effort, or pull, required on the level,

Then, $$F = f W_t$$

For instance, assuming $f = 20$, a force of 20 pounds will maintain the uniform motion of a car weighing 1 ton. If the car weighs 10 tons, the tractive effort required will be $F = 20 \times 10 = 200$ pounds.

37. Power Required to Maintain Motion.—To calculate the work performed by a force while moving a body through a certain distance:

Let F = force applied to body, in pounds;
s = distance through which body is moved, in feet;
W = work done, in foot-pounds.

Then, $$W = F s \qquad (1)$$

For example, if a force of 10 pounds is exerted to move a body through a distance of 10 feet, the work done will be $10 \times 10 = 100$ foot-pounds. If 33,000 foot-pounds of work is performed in 1 minute, the power exerted is 1 horsepower.

Let F = total force, in pounds;
S = speed, in miles per hour.

Then, since the speed, in feet per minute, is $\frac{5{,}280\,S}{60}$, the work done per minute is $\frac{5{,}280\,S\,F}{60}$, and

$$\text{H.P.} = \frac{\text{foot-pounds per minute}}{33{,}000} = \frac{5{,}280\,S\,F}{60 \times 33{,}000}$$

or, $$\text{H.P.} = \frac{S\,F}{375} \qquad (2)$$

EXAMPLE.—(*a*) Find the horsepower required to propel a car, weighing 10 tons, and moving at the rate of 10 miles an hour on the level, if the force necessary to keep the car in motion, neglecting wind resistance, is 200 pounds. (*b*) Find the current taken by the motor at 500 volts.

SOLUTION.—(*a*) The distance the car will move in 1 min. is $\frac{10 \times 5{,}280}{60}$ = 880 ft., so that the amount of work performed in 1 min. is 200×880 = 176,000 ft.-lb., which equals

$$\frac{176{,}000}{33{,}000} = 5{\cdot}33 \text{ H.P.} \quad \text{Ans.}$$

Or, applying formula 2,

$$\text{H.P.} = \frac{10 \times 200}{375} = 5{\cdot}33$$

(*b*) As there are 746 watts in 1 H.P., and the line pressure is 500 volts, the current required, neglecting losses in the motors and control gear, is

$$\frac{746 \times 5{\cdot}33}{500} = 8 \text{ amperes, nearly.} \quad \text{Ans.}$$

38. Effect of an Incline.—The steepness of an incline may be expressed as the ratio of the vertical rise in travelling a certain distance to the distance travelled. Or, if $a\,b$, Fig. 13, represents

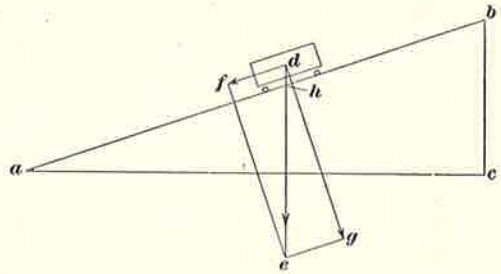

FIG. 13

the gradient and $a\,c$ is a horizontal line, the steepness of the gradient may be expressed by the ratio $\frac{b\,c}{b\,a}$. In addition to the force necessary to maintain motion on the level, to move a car up an incline there must be expended sufficient force to overcome the tendency of the car to run down the gradient. The weight of a car ascending the gradient may be represented by the line $d\,e$ acting vertically through the centre of gravity of the car. The weight may be resolved into the two forces $d\,f$ and $d\,g$, which are at right angles to each other. The force $d\,f$ is parallel to the gradient $a\,b$ and represents the force that tends to make the car run down the hill. The force $d\,g$ represents the reaction of the rail.

As the line $d\,f$ is parallel to the line $a\,b$, the angle $f\,d\,e$ is equal to the angle $a\,h\,e$; and as the line $d\,e$ is parallel to the line $b\,c$, the angle $a\,h\,e$ is equal to the angle $a\,b\,c$. Therefore, the angle $f\,d\,e$ is equal to the angle $a\,b\,c$. As the angles $e\,f\,d$ and $a\,c\,b$ are right angles, the triangles $e\,d\,f$ and $a\,b\,c$ are similar, and $\frac{d\,f}{d\,e} = \frac{b\,c}{b\,a}$, from which, $d\,f = d\,e \times \frac{b\,c}{b\,a}$. That is, the force tending to send

the car backwards down the hill is proportional to the weight of the car and to the steepness of the gradient.

39. Propelling Force Required on Rising Gradient.—The force that is required to move a car uniformly up a gradient is greater than that required to maintain motion on the level by an amount which depends on the gradient.

Let W_t = weight of car, in tons ;
G = gradient expressed as ratio of rise to length of incline, both in feet ;
F_w = force required to balance weight of car, in pounds.

Then, $$F_w = 2{,}240\, W_t\, G \qquad (1)$$

Let F_g = total tractive effort required to propel car up incline, in pounds ;
F = total force required to overcome resistance on level ;
f = tractive resistance per ton on level track, in pounds.

If the other quantities have the same values as in formula **1**, then the total force required to move a car up a gradient is

$$F_g = F_w + F = 2{,}240\, W_t\, G + f\, W_t \qquad (2)$$

40. Tractive Effort on Incline.—The steepness of a gradient is usually expressed by the distance which must be travelled along the gradient, in feet, in order to rise an amount equivalent to a vertical distance of 1 foot. Thus, a gradient of 1 in 100 means that there is a rise of 1 foot in travelling along the gradient a distance of 100 feet. From formula **1**, Art. **39**, it follows that the force required per ton of the weight of the car on such a gradient is $\frac{2{,}240 \times 1 \times 1}{100} = 22{\cdot}4$ pounds. To this amount, in order to obtain the total propelling force required to maintain motion, must be added the amount of the tractive resistance on the level. If the tractive resistance f is 20 pounds per ton, the total tractive effort required on the gradient is $F_g = 22{\cdot}4 + 20 = 42{\cdot}4$ pounds per ton.

41. The steepness of a gradient may be expressed as a percentage. Thus, if an incline is said to have a gradient of 3 per cent., it is meant that for every 100 feet travelled along the incline the track rises 3 feet. The percentage rise is sometimes referred to the horizontal distance travelled, but it is more general to refer all measurements to the distance measured along the incline. For all gradients usually met with in practice, it makes very little difference, so far as numerical results are concerned, which is taken, because the distance travelled along the incline is practically the same as the horizontal distance.

Thus, on a 1 per cent. gradient, the car rises 1 foot for every 100 feet travelled. The extra work done, due to the gradient, in propelling a car along it for a given distance is thus equivalent to lifting the weight of the car through one-hundredth of the distance travelled. Otherwise, for each ton that the car weighs, each 1 per cent. of the rise of the gradient has the same effect as the addition of $\frac{2240}{100} = 22{\cdot}4$ pounds to the tractive effort required on the level.

Let f_g = tractive effort, on incline, in pounds per ton ;
f = tractive resistance, on level, in pounds per ton ;
G_1 = percentage of gradient.

Then, $$f_g = f + 22{\cdot}4\, G_1$$

EXAMPLE 1.—What is the horsepower required to move a car weighing 10 tons up a gradient of 1 in 30 at the rate of 10 miles an hour, if the tractive effort is 20 pounds per ton on the level ?

SOLUTION.—Substituting in formula **2**, Art. **39**,

$$F_g = 2{,}240 \times 10 \times \tfrac{1}{30} + 20 \times 10 = 947 \text{ lb., nearly}$$

Substituting in formula **2**, Art. **37**, the power required is

$$\frac{10 \times 947}{375} = 25 \text{ H.P., approximately.} \quad \text{Ans.}$$

EXAMPLE 2.—If a tractive effort of 20 pounds per ton is required to maintain the uniform motion of a 10-ton car on a level track, what effort, per ton, will be required on a 5 per cent. grade ?

SOLUTION.—For each 1 per cent. of gradient, the force must be increased by 22·4 lb. per ton over the amount required on the level ; hence, applying the formula,

$$f_g = 20 + 22{\cdot}4 \times 5 = 132 \text{ lb. per ton.} \quad \text{Ans.}$$

ACCELERATION

42. Starting From Rest.—In the calculations that have been made so far, it has been assumed that the motion of the cars was uniform. It requires, however, much more power to start a car

and to get it running at full speed than to keep it in motion after it has been started. If the output of the motors were based merely on calculations relating to uniform motion, the motors would be too small to start the car rapidly from rest. In the early days of electric traction, the motors provided on the cars were too small, largely because the great increase of power required at starting had not been allowed for.

43. Power Required in Speeding Up.—In order to start a tramcar from rest and bring it up to speed, a certain amount of energy must be expended over and above that necessary to overcome the frictional or tractive resistance. The additional energy so expended is stored in the moving car as kinetic energy. The amount of kinetic energy which is stored in speeding up the car depends on the weight of the car and on the final speed. The power to be exerted during the starting period will depend, in addition, on the length of time allowed to attain full speed. In tramway problems, the rate at which the speed of a car is increased (*acceleration*) or decreased (*retardation*) may be expressed in feet per second per second, or in miles per hour per second. For example, if the acceleration is $1\frac{1}{4}$ miles per hour per second, in each second the speed of the car is increased by $1\frac{1}{4}$ miles per hour. If the car starts from rest, at the end of the first second it will be moving at the rate of $1\frac{1}{4}$ miles per hour, at the end of the second second, at $2\frac{1}{2}$ miles per hour, and so on.

44. Speed and Power Curves.—In Fig. 14 are shown typical speed and power curves for an electric train with an equipment capable of producing rapid acceleration. These are applicable also to the case of an electric tramcar, but while the curves for the latter will be similar in form and principle, the quantities will be smaller. Curve *A* shows the relation between speed and time. The letters *M.P.H.*, found at the left side of the diagram, mean *miles per hour* and refer to the numbers below. Curve *B* shows the total current supplied, and curve *C* the voltage. Starting from a standstill, the speed increases at an almost uniform rate up to 25 miles per hour; the curve then bends over and the rate of increase in speed, namely, the **acceleration,** becomes less until at $37\frac{1}{2}$ miles per hour the curve has become

nearly horizontal; the speed is then nearly uniform and the acceleration has become practically zero. After 93 seconds, the current is shut off and the train coasts along, by virtue of the energy stored in it, but with gradually decreasing speed. The brakes are applied at the latter end of the run and the train is retarded and finally brought to a stop, as indicated by the straight sloping line at the right of the figure.

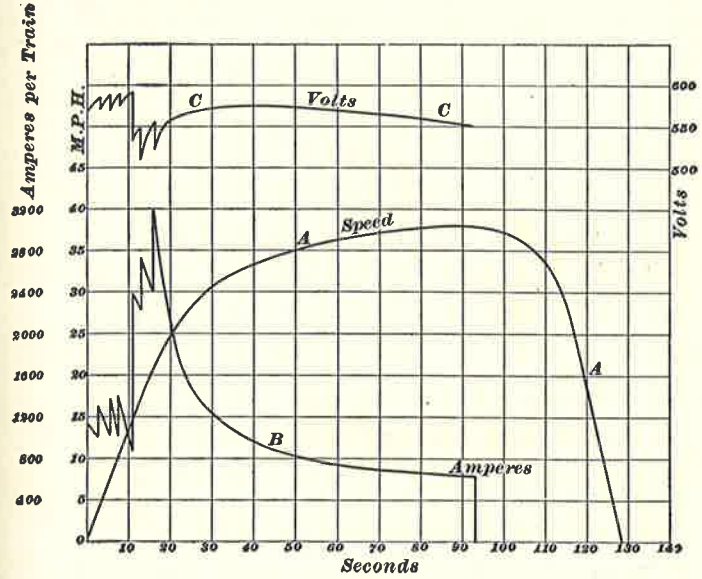

FIG. 14

45. When the train is started with all the starting resistance in series with the motors, the total current is about 1,100 amperes. As the resistance is cut out, the current varies, as shown by the notches in the curve, during the first 10 seconds; the motors are then thrown in parallel and the total current rises to nearly 2,400 amperes, after which it further increases to 3,200 amperes, as the resistance on the parallel notches is cut out. Up to this point the current in each motor has remained approximately constant and the tractive effort has, therefore, been nearly constant. The tractive resistance is also approximately constant for moderate speeds, with the result that the speed is almost

uniformly accelerated from 0 to 25 miles per hour during the first 20 seconds. The average acceleration during this interval is thus $1\frac{1}{4}$ miles per hour per second. As the speed increases beyond 25 miles per hour, the current rapidly diminishes and the tractive effort also diminishes. The acceleration therefore decreases, and when the current has dropped to about 650 amperes the speed has become nearly uniform. The tractive effort is then wholly utilized in overcoming the train resistance; during the acceleration period a large part of the total effort was used in increasing the speed and thereby storing energy in the train, and the remainder went to overcome the train resistance.

46. Force Required to Produce Acceleration.—The force F_a required, in addition to that necessary to overcome the tractive resistance and forces due to inclines, in order to make a car increase its rate of speed, is easily calculated.

Let m = mass of car;
a = acceleration.

Then, $$F_a = m\,a \qquad (1)$$

But m equals the weight w of the car divided by the acceleration g due to gravity; hence,

$$F_a = \frac{w}{g}\,a \qquad (2)$$

If w is expressed in pounds, g in feet per second per second, and a in feet per second per second, F_a will be the force, in pounds, and $F_a = \frac{w}{32{\cdot}2}\,a$, since g is equal to 32·2 feet per second per second. Usually, in traction calculations, the weight of the train or car is expressed in tons instead of pounds, and the acceleration in miles per hour per second instead of feet per second per second. One mile per hour = 1·467 feet per second and 1 ton = 2,240 pounds. If, then, A is the acceleration in miles per hour per second, the number of feet per second per second will be 1·467 A; and if W_t is the weight of the car, in tons, the number of pounds will be 2,240 W_t. The equation will then become

$$F_a = \frac{2{,}240\,W_t}{32{\cdot}2} \times 1{\cdot}467\,A$$

or,

$$F_a = 102\,W_t\,A \qquad (3)$$

EXAMPLE.—If an electric car weighs 10 tons, what accelerating force must be exerted to bring the car from a standstill up to a speed of 12 miles an hour in 15 seconds, assuming the acceleration to be uniform during this period?

SOLUTION.—The acceleration A is $\frac{12}{15}$ = ·8 mi. per hr. per sec. W_t = 10 tons; hence, from formula **3**,

$$F_a = 102 \times 10 \times {\cdot}8 = 816 \text{ lb.} \quad \text{Ans.}$$

47. Total Driving Force During Acceleration.—From formula **3**, Art. **46**, the tractive effort necessary to produce an acceleration of 1 mile per hour per second is 102 pounds for each ton weight of car. The relation between the acceleration, in miles per hour per second, and the accelerating force necessary to produce it, in pounds per ton, is shown in Fig. 15. It must be remembered that this accelerating force is additional to the force required to overcome the train resistance. Again, whenever a train is started, two kinds of inertia must be overcome; that is, kinetic energy is stored in two ways. The train must be made to move horizontally, the force required for this acceleration being given by formula **3**, Art. **46**, and a certain amount of

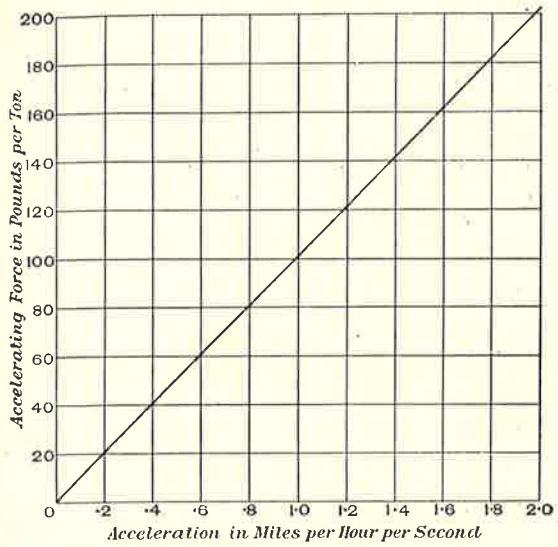

FIG. 15

energy is required to overcome the inertia of, or to be stored as kinetic energy in, the rotating parts, such as armatures, wheels, gears, and axles; this may amount to 8 or 10 per cent. additional to the force given by the formula. Therefore, taking the rotational inertia into account, formula **3**, Art. **46**, should be written

$$F_a = 110\, W_t\, A$$

Thus, if the force required to overcome the tractive resistance is taken as 20 pounds per ton, for moderate speeds on a good track, and if the force required to produce both rotational and linear acceleration is 110 pounds per ton for an acceleration of 1 mile per hour per second, the total tractive effort required to speed up the car at this rate will be 130 pounds per ton.

48. Limit of Adhesion.—The maximum tractive effort that can be applied at the rail surface is limited by the slipping of the wheels on the track; therefore, the possible acceleration that can be imparted to a car cannot exceed a certain maximum amount. There is also a certain maximum steepness of the incline that a car can ascend. The steepness of this incline must be such that the **adhesion** or the maximum tractive effort which can be exerted by the motors without wheel slippage is equal to the force tending to send the car backwards down the hill. The adhesion between the wheels and the rails depends on the total weight on the driving wheels and on the coefficient of friction between the wheels and track. The latter varies greatly with the condition of the rails, and also with the kind of car wheels. It is considerably less for wheels with chilled-iron tires than for those with steel tires. As a safe outside figure, the adhesive force may be taken as about 15 per cent. of the weight on the driving wheels. Thus, the maximum tractive effort that can be exerted without causing the wheels to skid may be taken as $2{,}240 \times \cdot 15 = 336$ pounds per ton of weight on the driving wheels.

49. It should be noted particularly that the weight referred to is only that portion of the total weight which is carried on the driving wheels. In the case of a single-truck car having two motors, all the wheels are driving wheels and the whole weight therefore rests on them; hence, this style of car is well adapted

for hill climbing and running on slippery tracks. If the cars are built with double trucks and two motors, the weight resting on the driving wheels will not be more than 55 to 70 per cent. of the total weight, thus limiting the maximum tractive effort to some figure between 185 and 235 pounds per ton of weight of car. If the cars have double trucks with four motors, one on each axle, the whole of the weight is supported on the driving wheels; hence, four-motor equipments are desirable for tramways in hilly localities using double-truck cars. For most lines with moderate gradients, however, two-motor equipments usually give sufficient adhesion.

50. Steepest Incline on Which Car Will Start.—If the adhesion and the tractive resistance of any car are known, the steepest gradient on which the car will start may be ascertained by calculation.

Let f' = tractive force, in pounds per ton of weight of car, necessary to start car on level;
G = gradient expressed as 1 divided by length, in feet, of incline for 1 foot rise;
W_t = weight of car, in tons;
b = ratio of adhesive force to weight on the driving wheels
c = ratio of weight on the driving wheels to the total weight.

Then the actual weight on the driving wheels, in pounds, is $2{,}240\ c\, W_t$; the total adhesive force is $2{,}240\ c\, W_t\, b$; the total force required for starting on an incline of which the gradient is G is $2{,}240\ W_t\, G + f'\, W_t$. If the tractive effort and the adhesive force are equal, then $2{,}240\ c\, W_t\, b = 2{,}240\ W_t\, G + f'\, W_t$, and $G = \dfrac{2{,}240\ c\, W_t\, b - f'\, W_t}{2{,}240\ W_t} = c\, b - \cdot 00045\, f'$

About 70 pounds per ton is a fair value for the tractive effort f' required to start a car on the level under ordinary conditions; if, however, the acceleration required is very great, the effort required during the time that the car is gaining speed may be much higher than this. The greatest acceleration obtainable will be limited by the wheels skidding.

EXAMPLE.—If 65 per cent. of the weight of a car is supported on the driving wheels and if the adhesive force is 15 per cent. of the weight on the driving wheels, what is the maximum grade on which the car can start without the wheels skidding, assuming that it requires an effort of 70 pounds per ton of weight of car to start on the level ?

SOLUTION.—In this case, $c = \cdot65$, $b = \cdot15$, and $f' = 70$. Then, from the formula,

$G = \cdot65 \times \cdot15 - \cdot00045 \times 70 = \cdot0975 - \cdot0315 = \cdot066$, or $\frac{1}{15}$, nearly

That is, the wheels will skid if the gradient exceeds 1 in 15. Ans.

POWER CONSUMPTION

51. Size of Units in Power Station or Substation.—In order to determine the size of the power station or substation units, it is necessary to know the maximum number of cars it is possible or desirable to run and the average current which each car will take. The number of the cars depends on the frequency of the service, the length of the line, and the average speed ; the average current of each car depends on the type of car and the topography of the road as regards its gradients and the number of curves. The frequency of the service on any route requires a close preliminary study of the district to be served, and a subsequent adjustment to suit all the varying conditions which soon make themselves apparent after the opening of the line. The units installed in the power station or substation should be sufficient to meet the traffic at the busiest hours with a safe margin of spare plant in case of breakdown. For dealing with special occasions, such as holidays, occurring only two or three times a year, all the plant should be utilized, as it is not economical to provide spare plant for the sake of 3 or 4 days in the year. Tramway motors in the British Isles are usually between 25 and 35 horsepower, two motors being generally fitted to each car. The exceptions to this standard arrangement are in some small systems, where only one motor may be fitted, and also where double-truck cars are operated in hilly districts ; in this case, four-motor equipments are sometimes used.

52. Speed of Cars.—The average speed of the cars will usually be from 6 to 8 miles an hour, depending on the amount of traffic carried and the busyness of the thoroughfares through which the

line passes. Before any line is open to the public, a Board of Trade inspection is made, with the object of fixing the maximum permissible speeds to be allowed on the different portions of the route, and to make regulations for compulsory stops at dangerous points. At curves and crossings, the speed may probably be limited to about 4 miles an hour, while in wide streets and with cars fitted with powerful magnetic brakes a maximum speed up to 16 miles an hour may be allowed. Still higher speeds may be allowed over private rights-of-way.

53. Average Current Per Car.—The average current taken from a 500-volt trolley wire by a tramcar under ordinary conditions may roughly be taken as 1·5 amperes per ton of weight, including passengers. A single-truck car weighs from 8 to 10 tons and a double-truck car from 11 to 15 tons. The weight of passengers may be allowed for at the rate of a ton for 15, so that a single-truck car carrying 50 passengers will probably weigh from 11 to 13 tons, and a double-truck car with 70 passengers from 16 to 20 tons. The average current required for a single-truck car will therefore be from 17 to 20 amperes, and for a double-truck car from 24 to 30 amperes. These figures will be found approximately correct for tramway systems where the rolling stock and track are in fairly good condition and the gradients and curves are not abnormal. Where specially heavy gradients must be climbed, due allowance would have to be made. Where long and steep inclines occur, the question of regenerative control, by which energy is returned to the trolley wire from cars descending the hills, is worthy of careful consideration.

54. For example, suppose that a tramway system which is 10 miles long is so situated that it may be economically supplied from one centre. A 5-minute service is to be arranged, the average speed of the cars being 8 miles per hour and the average current consumption per car being 20 amperes. The distance apart of the cars, that is, the distance run by any one car in 5 minutes, will be $8 \times \frac{5}{60} = \frac{2}{3}$ mile. The total number of cars on both up and down tracks will therefore be $\frac{2 \times 10}{\frac{2}{3}} = 30$ cars.

TABLE I

PARTICULARS OF ELECTRIC TRAMWAY EQUIPMENTS

Number of System	Length of Route Miles	Length of Track Miles	Population Served	Track			Cars			Power Station	
				Gauge		Maximum Gradient 1 in	Speed of Cars		Number of Cars	Number of Generating Sets	Total Output Kilowatts	Type of Engine
				Feet	Inches		Average Miles Per Hour	Maximum Miles Per Hour				
1	7·25	13·25	83,000	4	0	16	7	8	36	4	400	Vertical high-speed
2	5·5	9·0	91,000	3	6	17		12	22	3	550	Vertical high-speed
3	14·95	25·3	110,000	3	6	9	5½	16	45	4	675	Three horizontal tandem slow-speed One vertical high-speed
4	13·52	23·53	119,700	4	8⅛	13·5	7		50	7	1,625	Vertical high-speed
5	10·5	17·2	120,000	4	8½	16	8	12	30	2	600	Horizontal slow-speed
6	28	35·5	120,000	4	7⅝	11	7	12	70	4	2,200	Vertical slow-speed
7	17	28·34	162,000	4	7⅜	9·7	8	14	53	4	1,150	Three horizontal slow-speed One vertical high-speed
8	5	9·5	165,500	4	8½	16·5	10	15	14	3	500	Vertical high-speed
9	14·5	28·5	211,500	4	7⅜	17	6	14	100	5	2,075	One vertical high-speed Four vertical slow-speed
10	20	37	240,200	4	8½	18	7½	16	140	4	2,500	Vertical slow-speed
11	16·25	26·88	275,600	4	8½	20		12	116	6	1,560	Vertical high-speed
12	54·25	92·5	300,000	5	3	12		8	331	7	5,000	Six vertical slow-speed One steam turbine
13	40·7	74·7	463,200	4	8⅛	9·5	6¾	16	279	7	4,440	Three horizontal slow-speed Three vertical slow-speed One vertical high-speed
14	31·2	96·6	477,100	4	8⅛	18	7·3	16	270	8	6,150	Five horizontal slow-speed Three steam turbines
15	95	189·5	1,050,000	4	7⅜	11·9	7½	11¾	776	6	10,000	Vertical slow-speed

The total average current will be $30 \times 20 = 600$ amperes. If the station voltage is 550, the total demand on the station under normal conditions will be $600 \times 550 = 330{,}000$ watts $= 330$ kilowatts. A satisfactory arrangement of the power station to supply such an output is to install three generating units of 200-kilowatts capacity each, making a total of 600 kilowatts installed. Under normal conditions, this will provide one spare unit, all three units being operated on specially busy days; the arrangement will also allow one 200-kilowatt unit to run during the quiet periods of the day, two units being run under normally busy conditions. If two units of 350 kilowatts each are installed, 50 per cent. of the whole plant will be provided as spare instead of only $33\frac{1}{3}$ per cent. as when divided into three units; moreover, a larger unit than necessary will have to run during the period of light load. Economy both of capital and running expenses is thus gained by dividing up the plant into three units instead of into two units only.

55. Equipment of Typical Tramways.—Certain particulars of the track, cars, and power stations of a number of British tramway systems are given in Table I. The reference number of the system, length of route, the equivalent length of single track, and the population served are given in the first four columns; the tramways are arranged in the order of the populations served. The gauge and maximum gradient of the tracks are given in the succeeding columns, these are followed by the average speed attained by the cars and the maximum speed permitted by the Board of Trade, and the number of cars in use on the system. The number of the generating sets installed at the power station, their total output, and the type of engine driving the generators are then given. Vertical high-speed engines are largely used for the smaller sizes of generating sets, while for the larger units steam turbines are in some cases installed instead of large, slow-speed reciprocating engines.

56. Costs.—The generating works costs obtained on the different tramway systems in Great Britain vary from ·35d. to 1d. per kilowatt-hour; where current is purchased, the price paid varies from 1d. to 2d. per unit. Table II gives the power

TABLE II

POWER CONSUMPTION AND COSTS OF ELECTRIC TRAMWAYS FOR 1 YEAR

Number of System	Number of Car-Miles Run	Number of Passengers Carried	Number of Units Used	Units Used Per Car-Mile	Works Costs Per Unit Generated, in Pence				
					Fuel	Labour	Oil, Water, and Stores	Maintenance and Repairs	Total Works Costs
1	912,492	7,841,468	1,061,150	1·16	·41	·26	·02	·03	·72
2	580,018	5,452,743	949,351	1·64	·30	·18	·03	·10	·61
3	1,099,164	8,098,042	1,689,085	1·54	·37	·17	·03	·08	·65
4	1,278,015	12,124,297	2,496,077	1·95	·42	·12	·05	·05	·64
5	924,609	8,529,951	1,652,207	1·79	·21	·07	·02	·10	·40
6	1,998,185	17,434,724	4,500,051	2·25	·21	·08	·01	·12	·42
7	1,648,913	12,905,378	2,632,398	1·60	·30	·13	·04	·03	·50
8	1,281,552	16,367,911	2,437,428	1·90	·34	·14	·03	·05	·56
9	2,361,347	21,735,613	2,337,733	·99	·32	·14	·05	·03	·54
10	3,334,136	27,411,286	6,125,030	1·84	·21	·04	·12	·02	·39
11	3,379,117	32,958,883	4,334,049	1·28	·30	·11	·02	·22	·65
12	7,730,097	52,661,027	11,287,368	1·46	·27	·10	·02	·05	·44
13	7,364,305	76,356,031	13,373,958	1·82	·22	·07	·02	·08	·39
14	7,828,794	76,215,618	14,024,006	1·79	·24	·07	·02	·03	·36
15	20,802,797	221,744,569	25,944,010	1·25	·16	·10	·02	·07	·35

consumption and cost of power for the electric-tramway systems that were described in Table I. The number of passengers carried on each system during 1 year is shown. The energy consumption of the cars, in units per car-mile, has been calculated from the number of car-miles run and the number of units used during the year. The works costs, in fractions of a penny per unit generated, are made up of the costs for fuel; labour; oil, water, and stores; and maintenance and repairs. The works costs do not include any management expenses or capital expenses for interest on capital or depreciation of plant; these must be added to the works costs to obtain the total power costs.

57. Combined Lighting and Traction Generating Stations. The question of combining lighting and traction stations for economical working is one which has been greatly discussed; it is now generally admitted that, where possible, the lighting and traction loads should be controlled from one station. The advantages are more apparent in small stations than in large, but even in Glasgow, where a 10,000-kilowatt station was put down to supply the tramway system, it has been found advantageous to link it with the lighting stations, in order to interchange power during times of heavy load and so keep the capital and operating costs of both systems as low as possible.

SITUATION OF POWER HOUSE

58. Supply of Coal and Water.—When a power station is erected solely for traction purposes, the conditions which govern its situation are the facilities for obtaining coal and water and the necessity of keeping the station as near as possible to the position of most economical distribution; that is, generally, as near as possible to the centre of the load. Due regard must be paid to the cost of land and also to the class of neighbourhood; if erected in a residential locality the land will be more expensive and the supply authority are liable to actions at law for the nuisances caused by smoke and noise. The banks of canals and rivers are the most satisfactory positions, as the coal can be

brought up in barges and a supply of cold water for condensing is always at hand. The large power station for the Glasgow tramways is erected on the banks of a canal, while the stations for the London County Council tramways and for the London electric railways are on the banks of the Thames. Where such a site for the power station is not available, ponds must be made, and the condensing water from them must be used over and over again. Cooling towers and fans for cooling the water must also be installed and maintained at considerable cost. The questions of condensing and the provision of an adequate supply of cold water for this purpose are two of the most important considerations in modern power stations fitted with steam turbines, as the best possible vacuum is necessary to run these machines at a high efficiency.

59. Determination of Centre of Load.—The generating station should be placed as near as possible to the centre of the system which it will supply. By this is meant the centre of the load or traffic. Since underground cables must generally be used to convey the power from the generating station to the various sections of the tramway route, a part of the power generated will be lost in them. If the cables are not of sufficient size, they will cause a loss of voltage that will make itself very strongly felt in its effect on the speed of the cars and also on the amount of heat developed in the motors. The loss of power in transmission in each feeder depends on the resistance of the line and the amount of current that it must carry. Hence, even if all the feeders are of equal length, the losses in them may vary. The centre of the load may not be the geographical centre of the system ; in fact, these two centres may seldom fall in the same place. The true load centre may be found by calculation in the same way as the centre of gravity of any system of heavy bodies. The geographical centre depends on the number of miles of track and how these are disposed ; the load centre depends on how the load is distributed.

60. In Fig. 16 *A B* represents 10 miles of track that is free from gradients and sharp curves and on which a certain number of cars *1*, *2*, *3*, *4*, etc., of about the same weight and equipped

with motors of the same size, run at regular intervals. The geographical centre, or centre of mileage, is in this case at a point *P* midway between the two ends, so that there is 5 miles of the route on each side of it. In this case, the load centre also is at *P* ; for, suppose that all the cars, except the two on the extreme ends, are running at full speed. Since the track is level and the cars and motors are alike, they will all take about the same power ; and since the loads are evenly distributed throughout the length of track, the centre of gravity of the system will fall on the centre line *c l*. So, also, if all the cars, except the two end ones, are supposed to stand still or to coast along with the power off and the two end ones start at the same time, there

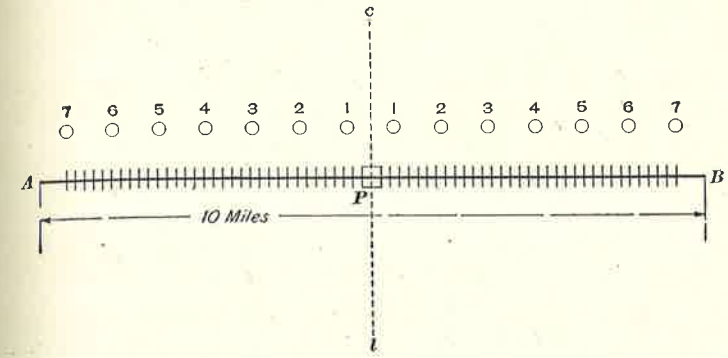

Fig. 16

will be similar loads at both ends of the line and the point *P* will still be the centre of load ; this, therefore, is the point where the power house should be placed.

61. It is not implied that the load, even on such a simple layout, will always be as evenly distributed as in the ideal case just described, for such a condition will be the exception rather than the rule. Suppose that *A*, Fig. 16, is in the outskirts of a large city, the centre of which is at *B* ; then, in the morning and evening, when people are going to and returning from work, the load leans toward the city end of the line at *B*, but during the rest of the day it is uniformly distributed. Again, suppose that from the middle of the line to *B* is uphill. The motors of

those cars that are ascending the hill will be called on to do more work than those travelling on the level toward A, so that the ideal site for the station will be shifted toward B. In this case, the mileage centre remains the same as before, but the load centre is changed.

62. Influence of Future Extensions.—In fixing the site for the power station, future extensions and the probable increase in traffic incidental to the development of outlying districts should be borne in mind and the site selected accordingly. Suppose, for example, that the full line $A\,B$, Fig. 17, represents 5 miles

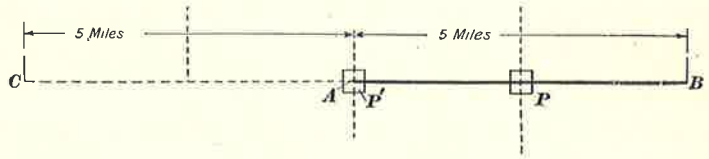

FIG. 17

of track put down at the first building of a given tramway, and that, in accordance with the demand existing at that time, the power station was put at P, the centre of load for $A\,B$, which is supposed to be level track. Suppose, however, that the tramway has been extended at a later date to a point C, so that now $A\,B = A\,C$. When the district through which $A\,C$ runs becomes built up, the load density will be quite as great on the new part of the route as on the old, in which case, assuming the load to be distributed fairly evenly throughout the distance $B\,C$, the proper place for the power house would now be at the point P', midway between B and C. So long as $A\,B$ constituted the whole road, the power house situated at P was at the centre of an evenly distributed load, and the same loss of power would attend the transmission of a given amount of power to one end of the line as to the other. With the opening of the extension to $A\,C$, however, the power house at P is only $2\frac{1}{2}$ miles from one end B and the distance $P\,C$, or $7\frac{1}{2}$ miles, from the other end C.

63. With the arrangement just described, the total transmission losses to all parts of the system are greater, in any case, than if the power station were at P', Fig. 17. Moreover, should

a large number of the cars, through trouble of some sort, be held up near the far end C of the line, the voltage drop in transmission, due to the great distance and to the large current taken in trying to start all the cars at once, will seriously delay the cars in getting up to time again. If the station were put at A in the first place, it would be at one end of the line as long as $A\,B$ was the whole road, and, for the time being, would not be at the centre of load; but if the construction of the extension $A\,C$ were only a matter of time, it would be far better to put the station at A in the first place, notwithstanding the extra line loss at first, due to want of balance on the shorter line, with a view of obtaining the best results when the extension is put into operation.

64. Large Tramway System.—If a tramway system is much larger than that just considered, certain other factors make it desirable to place the power station away from the centre of the

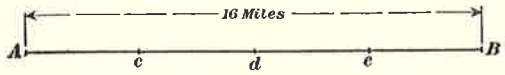

FIG. 18

load. These are due to the fact that the limiting distance for economical direct-current distribution is usually about 4 miles from the power station or substation. If the greater part of a given tramway system is included within this limit, only one distributing centre will be necessary, and the most economical position for it will be at the centre of the load. If the system extends along one line, perhaps 12 to 16 miles long, the most economical method of supply will possibly be with the addition of one substation; the power station will then be placed away from the load centre. For example, if $A\,B$, Fig. 18, is a route 16 miles long, on which c, d, e are points at 4-mile intervals, the best position of the power station will be near e, and the corresponding position of the substation will be near c. This will give each distributing centre a 4-mile radius to deal with. Due regard must be paid to the radius of economical direct-current distribution, and the substations and power station must be disposed of accordingly.

65. Alternating-Current Transmission and Direct-Current Distribution.—In the instance just given, the power station must generate both direct and alternating current, direct current for supplying the cars in the power-station radius and alternating current for transmitting to the substation. If some of the generators are constructed for alternating current and some for direct, at least one spare unit of each type must be provided. If the circumstances are such that it is desirable to avoid this, any one of the following arrangements are available: All the generating units may be constructed for alternating current, and the current for local distribution obtained from rotary converters and transformers placed in the power station; or direct-current generators may be installed and alternating current obtained by means of rotaries and transformers or motor generators. A third method is to put down both direct-current generators and alternators in connection with a reversible rotary converter. At times of light load, the rotary may be driven by transformed alternating current; it will then supply direct current for the local area as required; or it may be driven from the direct-current generators, when it will supply alternating current for transmission to the substation.

66. Conditions Affecting Choice of Site.—In deciding the best situation for the generating station, if it were only a matter of finding the probable centre of the load, the problem would be comparatively easy. But in many cases it is made very difficult, on account of several other considerations that enter into the question. A site where every pound of coal to be burnt under the boilers must be hauled to the power house, or where it is difficult to get water for the boilers and the condensers, is, of course, out of the question, even if it is the centre of the load. In many cases, a compromise must be made between conflicting conditions. Load conditions will point to one site, and good cheap water will point to another; but, in every case, the coal bunkers must be situated so that the coal may be conveyed directly into them from a canal barge or lighter, or from coal trucks that can be run alongside of them by means of a railway siding.

EXAMPLES OF SMALL TRAMWAY POWER STATIONS

STEAM-DRIVEN STATION

67. Power Station.—As the method of operating large and small tramways is nearly the same, so far as the details of the cars and the line construction are concerned, two typical tramway installations for a small number of cars are here given. The first of these installations is for a steam-driven power station; the second is equipped with oil engines. The first tramway system has 15 miles of single track laid on a route of 12 miles. There is a fairly easy route, with maximum gradients of 1 in 20 and curves of a minimum radius of 46 feet; the rail gauge is 4 feet 7 inches. There are twenty-six cars, of the double- and single-deck types, on four-wheeled trucks, each double-deck car being fitted with two 30-horsepower motors.

68. In Fig. 19 (*a*) and (*b*) are shown the power house and car sheds. The engineers' offices and stores occupy the front part of the power station (*a*). Behind these is the engine room. This is equipped with generators wound to give any pressure between 480 and 550 volts, for this station supplies both lighting and power. High-speed engines are direct-coupled to the generators. One set *a* has an output of 600 kilowatts, two *b*, *c* have an output of 175 kilowatts each, and one *d* has an output of 50 kilowatts. Two switchboards are used, one *e* controlling the lighting load and the other *f* controlling the traction circuits. In a large room over the offices, two sets of storage batteries are installed. The lighting battery is divided into two parts of 120 cells each, so as to supply the three-wire system with 480 volts between the outers; the traction battery contains 240 cells. An automatic reversible booster *g* works in conjunction with the traction battery to equalize the load on the generators. Two balancing booster sets *h*, *i* are used to balance the three-wire system of lighting distribution and to charge the lighting battery. Behind the engine room is the boiler room, which contains four Babcock water-tube boilers placed in two pairs *j*, *k*; four short steel

chimneys *l* are placed one behind each boiler. The coal bunkers *m* are arranged along the end of the boiler room and the feed-pumps are placed in a small room *n* at one side. The car shed and depot, Fig. 19 (*b*), is at present large enough for nine 28-foot

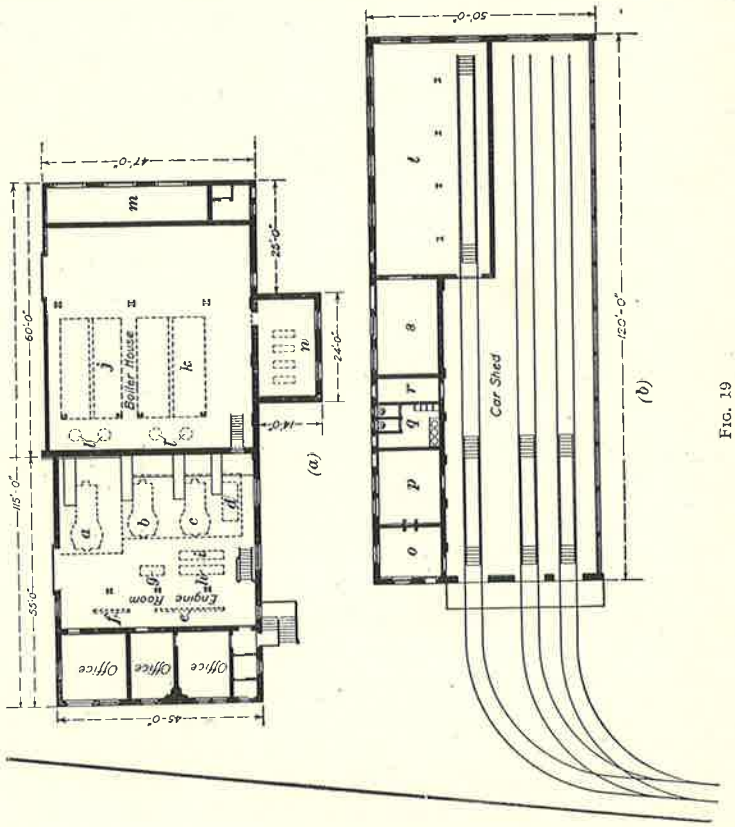

FIG. 19

cars, but may be extended. A ticket and time office *o*, men's room and lavatory *p*, *q*, sand shed *r*, stores *s*, and workshop *t*, occupy one side of the building.

OIL-DRIVEN STATION

69. In Fig. 20 is shown the car depot and plan for an oil-driven generating station. This generating station supplies a tramway which has 2 miles of double track and 8 miles of

single. The gauge is 3 feet 6 inches. The maximum gradients are 1 in 11, the sharpest curves have a 55-foot radius, and the maximum permissible speed is 12 miles an hour. There are thirteen double-deck cars on four-wheeled trucks, each fitted with two 40-horsepower motors, as the line is very hilly.

70. The power station, Fig. 20 (*b*), is divided into two parts, the engine and battery rooms. The engine room contains two

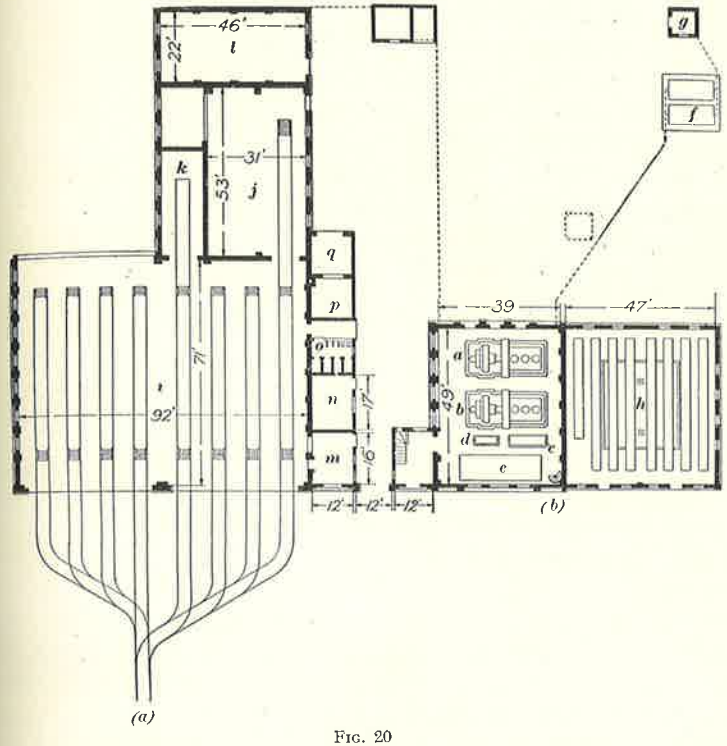

FIG. 20

240-brake-horsepower Diesel engines *a*, *b*, each direct-coupled to one 165-kilowatt direct-current generator. These sets run at a normal speed of 172 revolutions per minute. It also contains a battery booster *c* and a negative booster *d*, which is connected in the return circuit. The load is controlled by a switchboard *e* at one end of the engine room. The crude petroleum oil used

by the engines costs about £3 per ton, and the consumption per kilowatt-hour under normal conditions is guaranteed by the engine builders not to exceed ·7 pound. Therefore, taking into consideration that no firemen are employed and that there are no standby charges for keeping up steam in boilers, a plant of this kind will under certain circumstances prove more economical than a steam-driven plant of the same size. The crude oil is stored in oil tanks *f* some distance from the engine room. It is then pumped into smaller tanks in the engine room, as required for use, by means of a small electric pump in the pump house *g* near the oil tanks. The battery room *h* contains 260 cells, and has a capacity of 500 ampere-hours, or an output of about 250 kilowatts for 1 hour.

The car depot, Fig. 20 (*a*), consists of a car shed *i* and repair shop *j*, paint shop *k*, and stores *l*. In addition, there are a ticket office *m*, men's messroom *n*, lavatory *o*, sand dryer *p*, and sand store *q*. The car shed is arranged to hold sixteen cars.

TRAMWAY-STATION RECORDS

TYPICAL DAILY-LOG SHEET

71. Form of Daily Log.—In Fig. 21 is shown the **daily-log sheet,** or form, which is filled each day in a generating station supplying a combined traction and lighting load. It contains the record of the working of the station from 10 p.m. of one day to 10 p.m. of the next, the station being worked in three 8-hour shifts, which change at 6 a.m. and 2 and 10 p.m. The records for each day group themselves in four sections. The first section consists of half-hourly readings of the performance of the generating machinery, the load on the feeders, and data regarding the boilers and condensers. These readings show the variations of load on the station and the behaviour of the machinery throughout the day, and are recorded by the switchboard attendant on duty in each shift. Other sections include a shift report and a summarized statement of the results of the day's working ; these are usually entered by the shift engineer in charge of each shift.

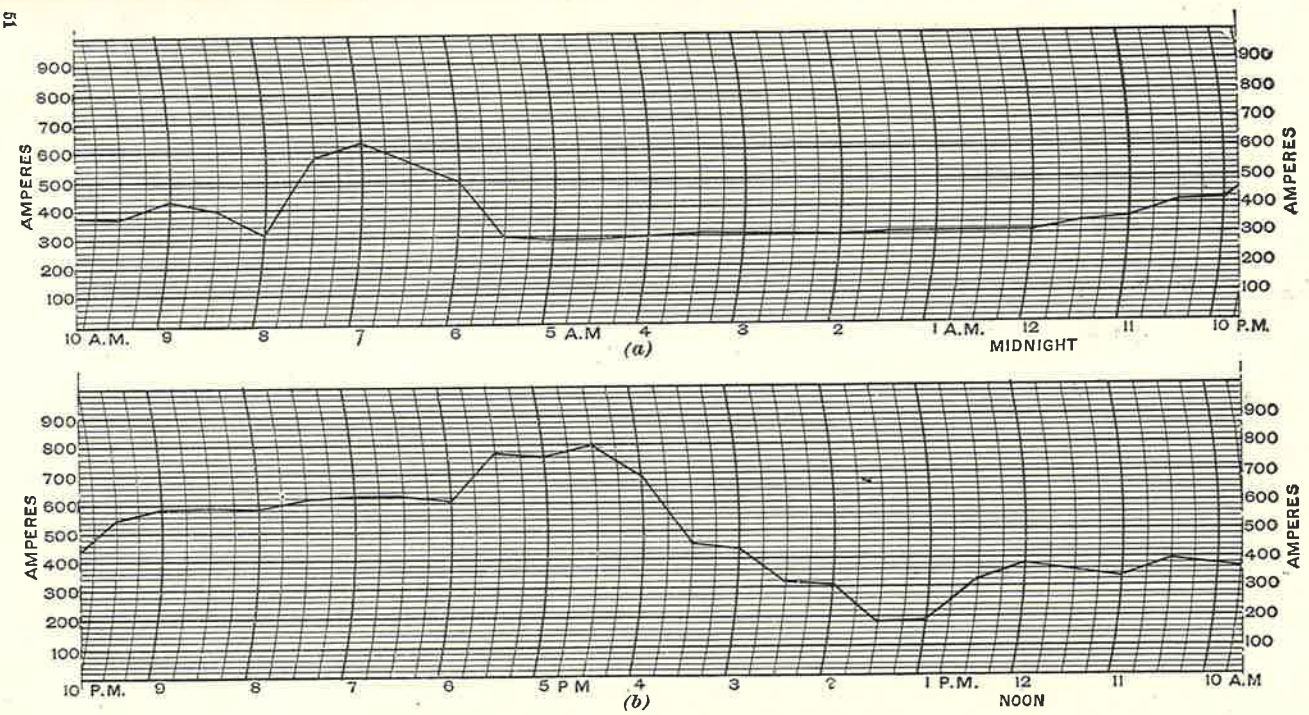
AMPERES
900
800
700
600
500
400
300
200
100
10 A.M.
9
8
7
6
5 A.M
4
3
2
1 A.M.
12
11
10 P.M.
MIDNIGHT
(a)
AMPERES
10 P.M.
9
8
7
6
5 P.M
4
3
2
1 P.M.
12
11
10 A.M
NOON
(b)

FIG. 22

The last section reports the statutory tests required by the Board of Trade.

72. Generating Machinery.—In the station from which the log shown in Fig. 21 is taken, there are three main direct-current generators, with a combined output of 1,000 kilowatts. The traction supply is at 500 volts on the trolley wire and the lighting supply is given on the three-wire system, with a declared pressure at the consumers' terminals of 460 volts between the outers. The generators are therefore designed so that they will develop 460 to 500 volts, for lighting, when running as shunt-wound machines, or will develop from 500 to 550 volts, for traction, when running as compound-wound machines. As shown in the log sheet, one generator is run on the lighting load; its readings are given on the sheet and are plotted in Fig. 22 (*a*) and (*b*); one generator takes charge of the traction load, indicated by *T*; the third machine is kept as standby or spare. The lighting load is especially heavy. The traction load is so variable that instrumental readings are not entered on the log sheet; a record is obtained, however, by means of a recording ammeter and is reproduced in Fig. 23 (*a*) and (*b*). In each case the curves, which are cut into halves for convenience, show the records for 24 hours.

73. Electrical Records.—The lighting of the power station and the motors driving the feed-pumps and other auxiliary machinery are connected to the three-wire bus-bars, and the current on the + and — sides is entered on the log sheet. The three-wire lighting system is balanced by means of a balancer consisting of three machines coupled together on one shaft. The end machines act as generators or motors, as shown by the + and — signs for the current flowing in them, according to the disposition of the lighting load on one side or the other of the three-wire system. The centre machine may also be driven as a motor from the traction bus-bars. When the traction load is lightest, between 12 o'clock midnight and 5 a.m., the traction generator is shut down, and the traction load is supplied by the centre machine running as a dynamo, while the end machines are motored from the lighting bus-bars. After the balancer readings, succeeding columns give the current in the outers and middle wire of the

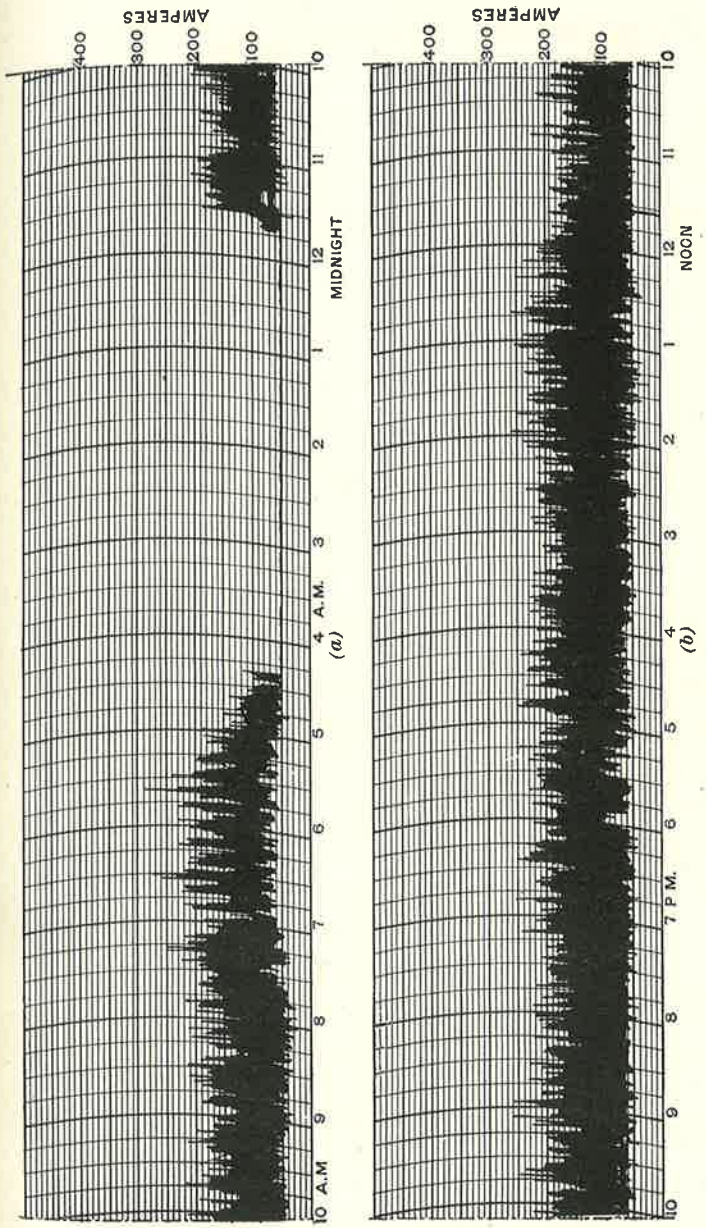

FIG. 23

lighting and general supply feeders, and the current taken by a rotary converter. The last-named machine is motored from the outers of the lighting bus-bars, and, on the alternating-current side, in conjunction with transformers, supplies alternating current for transmission to distant points of the lighting system. The pressure readings show the voltage across the outers of the lighting bus-bars, and the voltage between each outer and the neutral of pilot wires, run to the central point of the lighting load.

74. Steam Plant and Shift Report.—In order to keep a record of the operation of the steam plant in the generating station, one column of the log sheet is allotted to each of the four boilers, and ticks in the proper columns indicate which boilers are kept under steam throughout the day. The following columns show the variations of the boiler steam pressure, the hours during which the steam-driven and electrically driven boiler feed-pumps are working, and the temperature of the feedwater supplied from economizers 1 and 2. For the condensers, the vacuum is given in the equivalent inches of mercury, and the temperatures, in degrees Fahrenheit, of the circulating-water inlet, circulating-water outlet, and the air-pump discharge. The variation of these quantities with the variation of load throughout the day may be studied with advantage. The remarks under the heading of Shift Report show the times at which the generators are started up or shut down and when the switches are opened or shut.

75. Summary of Daily Results.—The section of the log sheet comprising the summary of the daily results is usually entered up by the third, or evening, shift engineer, and its main purpose is self-explanatory. Records are kept of the units generated by each generator, units used on works, and of the units sent out on the various feeders. If desired, the meter readings of the separate watt-hour meters may be entered on the daily log sheet, but otherwise a separate meter book may be kept. The records of maximum load, and of the coal and water used, are clear from the respective headings and the items entered thereunder. A space is reserved at the bottom of the sheet on which to enter the results, daily or weekly as the case may be, of the Board of Trade tests of the traction system.

TRAMWAY TRACKS

TRACK WORK

RAILS AND RAIL ADJUSTMENTS

PRELIMINARY CONSIDERATIONS

1. Necessity for Substantial Construction.—The track on which electric tramcars are to be run must be very substantially constructed. The car wheels drive the car by their reaction on the rails and cause much greater wear and tear than if the cars were hauled by a moving cable or by horses, because the rails are subjected to a grinding action whenever the wheels fail to grip them, and slipping occurs. In addition to this, the driving motors and control gear increase the weight of the car, and consequently the pounding which goes on at rail joints, points, and crossings. The permanent way as constructed for horse tramways was altogether too light for the heavy cars and the rapid acceleration introduced by electric traction, and the track as constructed to-day is as substantial as for main-line steam railways.

2. Gauge.—By the gauge of the track is meant the width between the rails, measured from the outer side of the groove in one rail to the outer side of the groove in the other rail, as shown at *a* in Fig. 1.

The greater number of tramway companies in Great Britain have adopted either the broad or the narrow gauge, the former

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